w/ revised figures 21 & 22

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PROGRESS REPORT III

RESEARCH STUDY ON STILLING BASINS, ENERGY DISSIPATORS, AND ASSOCIATED APPURTENANCES

SECTION 7

SLOTTED AND SOLID BUCKETS FOR HIGH, MEDIUM, AND LOW DAM SPILLWAYS

Hydraulic Laboratory Report No. Hyd-415

DIVISION OF ENGINEERING LABORATORIES

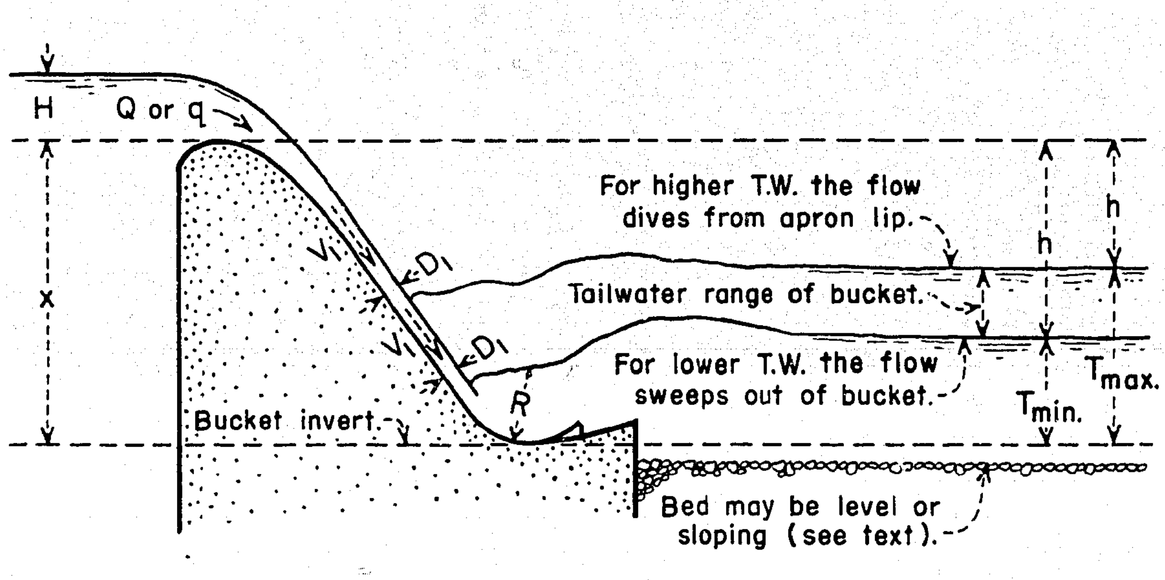
COMMISSIONER'S OFFICE
DENVER, COLORADO

July 1, 1956

Summary

The slotted bucket developed in this study for use as an energy dissipator at the base of a spillway is particularly suited to installations where the tail water is too deep for a hydraulic jump apron, or where a bucket structure is preferable to a longer hydraulic jump stilling basin. Charts and curves are presented in dimensionless form so that a bucket may be designed for most combinations of discharge, height of fall, and tail water range. The resulting bucket will provide self cleaning action to reduce abrasion erosion in the bucket arc, protection against undermining of the bucket and apron as a result of scour, and good vertical distribution of the flow leaving the bucket. The water surface downstream from the bucket may, for the lower tail water elevations, be somewhat rougher than desirable, however, making it necessary to consider the effects of possible riverbank erosion.

A schematic diagram of a spillway and slotted bucket containin definitions of the important dimensions is shown below:



A simplified version of the seven steps required to design a bucket is given below:

1. Determine Q, q (per foot width), V_1 D_1; compute Froude number from $F = \frac{V_1}{\sqrt{gD_1}}$ for maximum flow and intermediate flows. In some cases V_1 may be estimated from Figure 25.

2. Enter Figure 19 with F to find bucket radius parameter $\frac{R}{D_1 + \frac{V_1^2}{2g}}$ from which minimum allowable bucket radius R may be computed.

3. Enter Figure 21 with $\frac{R}{D_1 + \frac{V_1^2}{2g}}$ and F to find $\frac{T_{min}}{D_1}$ from which minimum tail water depth limit may be computed.

4. Enter Figure 22 as in Step 3 above to find maximum tail water depth limit, T_{max}.

5. Make trial setting of bucket invert elevation so that tail water curve elevations are between tail water depth limits determined by T_{min} and T_{max}. Check setting and determine factor of safety against sweepout from Figure 24 using methods of Step 3. Keep apron lip above riverbed, if possible.

6. Complete design of bucket using Figure 1 to obtain tooth size, spacing, dimensions, etc.

7. The sample calculations in Table VII, page 48, may prove helpful in analyzing a particular problem.

The procedures outlined above summarize the main considerations in the design of a slotted bucket. Other considerations are discussed in the report, however, and the entire report should be read before attempting to use the material given above.

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FIGURES

CONTENTS--Continued

TABLES

Foreword

This report, Progress Report III, is the third in a series of progress reports on research subjects included under the general title of this report. Progress Report II, published as Hydraulic Laboratory Report Hyd-399 which superseded Progress Report I, Hyd-380, contains 6 sections covering the following subjects:

Section 1--General Investigation of the Hydraulic Jump on a Horizontal Apron (Basin I)
Section 2--Stilling Basin for High Dam and Earth Dam Spillways and Large Canal Structures (Basin II)
Section 3--Short Stilling Basin for Canal Structures, Small Outlet Works and Small Spillways (Basin III)
Section 4--Stilling Basin and Wave Suppressors for Canal Structures, Outlet Works and Diversion Dams (Basin IV)
Section 5--Stilling Basin with Sloping Apron (Basin V)
Section 6--Stilling Basin for Pipe or Open Channel Outlets--No Tail Water Required (Basin VI)

Section 7 is contained in this report and covers Items 11 and 12 given in the "Scope" of the research program as originally planned and given in Progress Report II. Other numbered items will be completed and reported in future progress reports as time and funds permit.

The bucket tests described in this report are of recent origin, however, bucket tests in general have been made since about 1933. Some of the early tests were valuable in this study in that they helped to point the way for the later tests and eliminated certain bucket schemes from further consideration. These early tests were conducted by J. H. Douma, C. W. Thomas, J. W. Ball, and J. N. Bradley. Later tests were made by R. C. Besel, E. J. Rusho, and J. N. Bradley under the laboratory direction of J. E. Warnock. The final tests to develop the slotted bucket and generalize the design were made by G. L. Beichley under the supervision of A. J. Peterka and J. N. Bradley and laboratory direction of H. M. Martin. Most of the material contained in this report was submitted as a thesis for the degree of Master of Science, University of Colorado, by G. L. Beichley. All tests and analyses were conducted in the Bureau of Reclamation Hydraulic Laboratory, Denver, Colorado. This report was written by A. J. Peterka.

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Commissioner's Office--Denver
Division of Engineering Laboratories
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Hydraulic Structures and Equipment Section
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July 1, 1956

Laboratory Report No. Hyd-415
Compiled by: G. L. Beichley
A. J. Peterka
Submitted by: H. M. Martin

SECTION 7

SLOTTED AND SOLID BUCKETS FOR HIGH, MEDIUM, AND LOW DAM SPILLWAYS (BASIN VII)

INTRODUCTION

General

The development of submerged buckets has been in progress for many years and many types have been proposed, tested, and rejected for one reason or another. The bucket used at the start of these tests, the Grand Coulee bucket, therefore, was the result of many trials and experiences, both in models and in the field. The bucket was further developed for use at Angostura Dam by adding slots in the bucket and a short sloping apron downstream. After extensive laboratory tests showed that the Angostura bucket could not be improved in a practical way, tests were conducted to generalize the design so that proper bucket dimensions and limiting conditions could be determined for any installation. Some of the limits established during the tests had no sharp line of demarcation between acceptable and undesirable performance, consequently, the results of the tests reflect the judgment of the testing engineers. Every attempt was made to set the limits from a practical viewpoint so that the resulting structure would be economical to construct but would still provide safe operation for the extreme limits and satisfactory or better performance throughout the usual operating range. Strict adherence to the charts and rules presented will therefore result in the smallest possible structure consistent with good performance and a moderate factor of safety. It is suggested, however, that confirming hydraulic model tests be performed whenever: (a) sustained operation near the limiting conditions is expected, (b) discharges per foot of width exceed 500-600 second-feet, (c) velocities entering the bucket are appreciably over 100 feet per second, (d) eddy effects at the ends of the spillway result in poor flow conditions, and (e) waves in the downstream channel would be a problem.

Performance

There are two general types of roller or submerged buckets for spillways; the solid type developed for Grand Coulee Dam, Figure 1A, and the slotted type, developed for Angostura Dam, Figure 1B. Both types are shown operating in Figure 2 and are designed to operate submerged at all times with the maximum tail water elevation below the crest of the spillway. Both types also require more tail water depth (D_2) than a hydraulic jump basin.

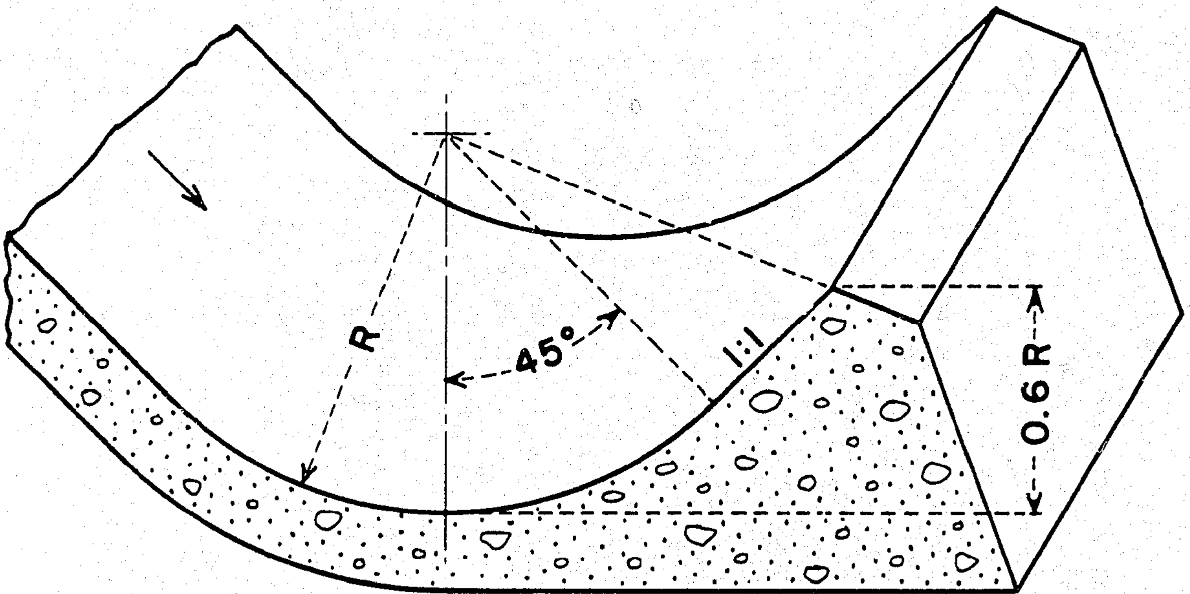
The hydraulic action and the resulting performance of the two buckets are quite different. In the solid bucket the high velocity flow, directed upward by the bucket lip, creates a high boil on the water surface and a violent ground roller that deposits loose material from downstream at the bucket lip. The constant motion of the loose material against the concrete lip and the fact that unsymmetrical gate operation can cause eddies to sweep material into the bucket may make this bucket undesirable in some installations. In the operation of the slotted bucket both the high boil and violent ground roller are reduced, resulting in greatly improved performance. Since only part of the flow is directed upward the boil is less pronounced. The part of the flow directed downstream through the slots spreads laterally and is lifted away from the channel bottom by the apron extending downstream from the slots. Thus, the flow is dispersed and distributed over a greater area providing less violent flow concentrations than occur with a solid bucket.

The tail water range over which the buckets will operate satisfactorily is less, however, with the slotted bucket than with the solid bucket. Sweepout occurs at a higher tail water elevation with the slotted bucket, and if the tail water is too high, the flow dives from the apron lip to scour the channel bed as shown in Figure 3. With the solid bucket, diving is impossible except perhaps in rare cases. In general, however, the slotted bucket is an improvement over the solid type and will operate over a wide range of tail water depths.

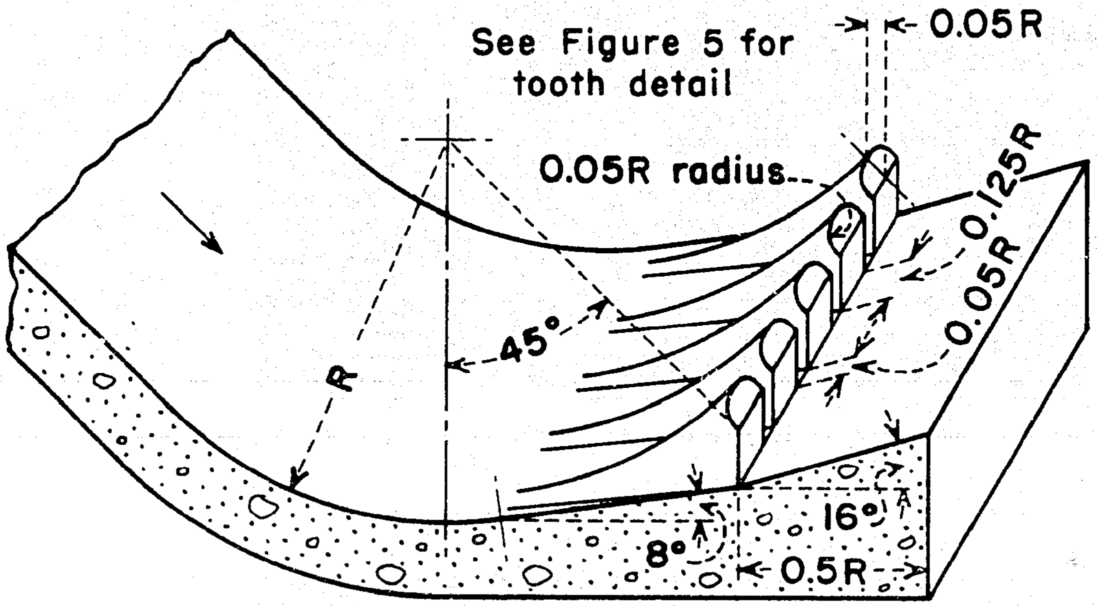
SLOTTED BUCKET DEVELOPMENT TESTS

General

The basic dimensions for the slotted bucket were determined from tests made to adapt the solid bucket for use at Angostura Dam.



A. GRAND COULEE TYPE SOLID BUCKET



B. ANGOSTURA TYPE SLOTTED BUCKET

SUBMERGED BUCKETS

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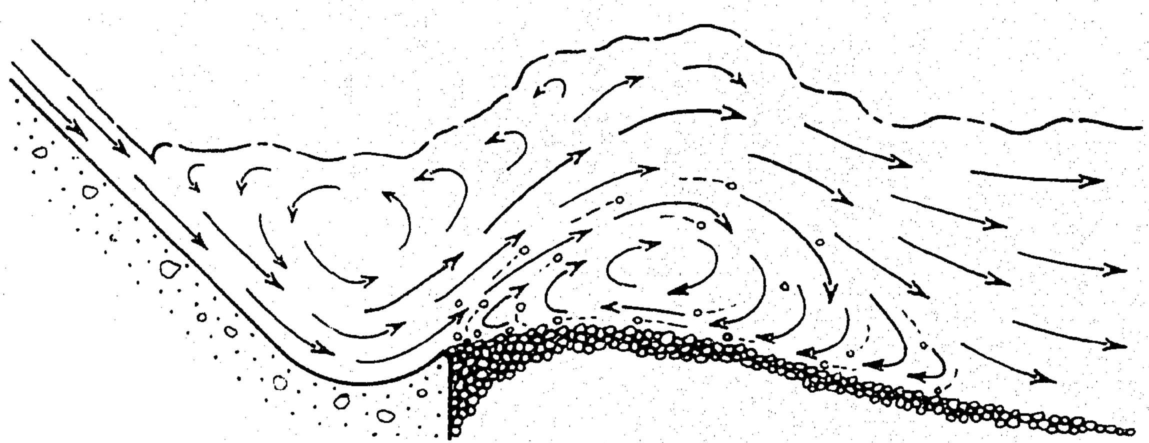
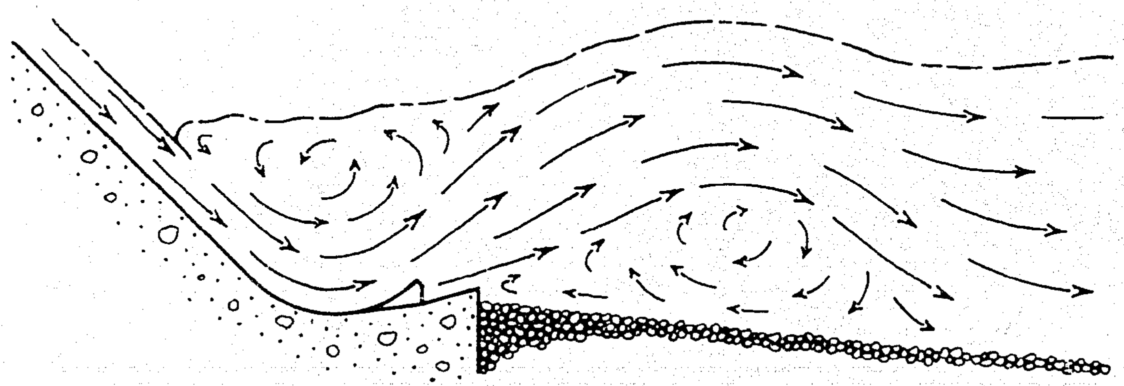
FIGURE 2



A. SOLID TYPE BUCKET



B. ANGOSTURA TYPE SLOTTED BUCKET

Bucket radius = 12", Discharge (q) = 3 c.f.s.,
Tailwater depth = 2.3'

PERFORMANCE OF SOLID AND SLOTTED BUCKETS

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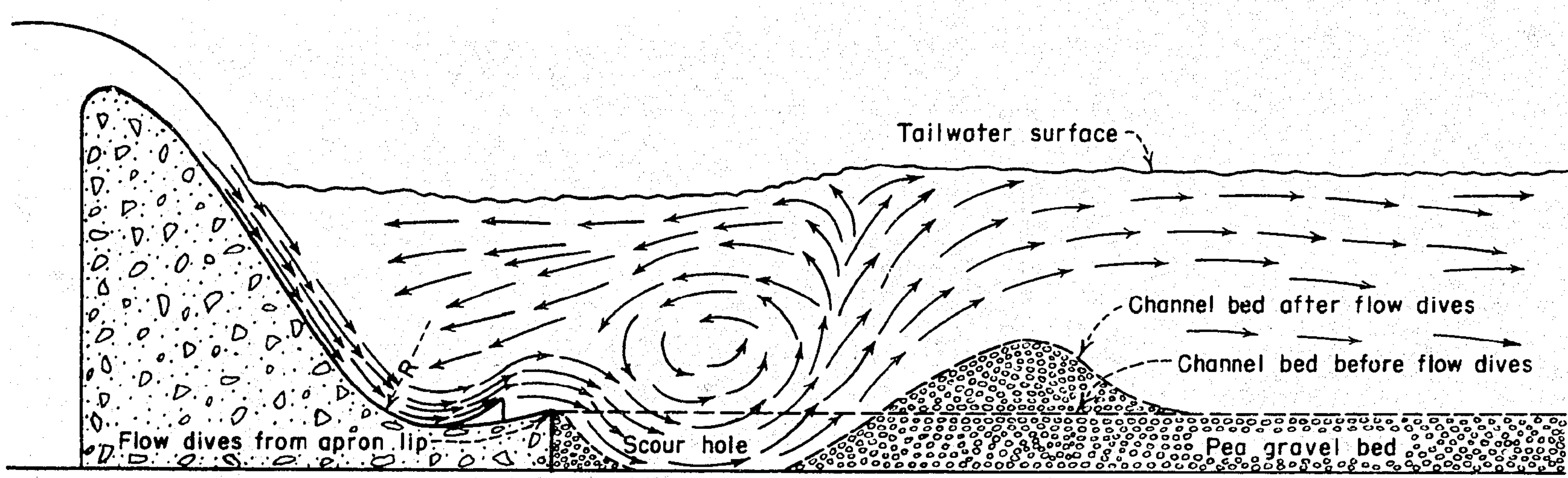

Note: The diving flow condition occurs with the slotted bucket only when the tailwater depth becomes too great.

DIVING FLOW CONDITION
SLOTTED BUCKET

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FIGURE 3

This study is reported in Bureau of Reclamation Hydraulic Report No. Hyd-192 and is summarized in the following paragraphs.

Development from Solid Bucket

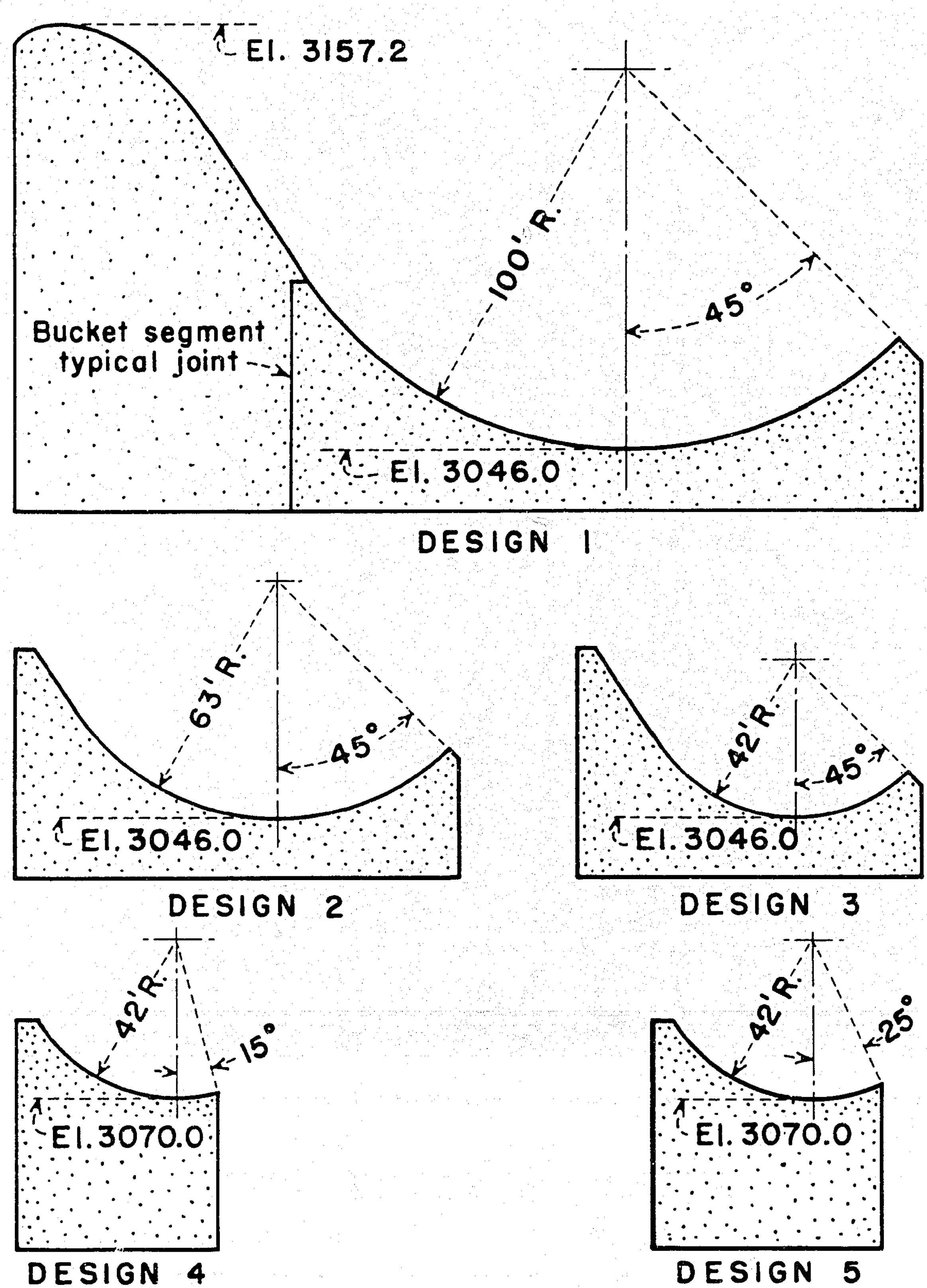
The first stage in the development was to determine the radius of bucket required to handle the maximum design flow and to determine the required elevation of the bucket invert for the existing tail water conditions. Solid type buckets shown in Figure 4 were used in the model to determine these approximate values since the slotted bucket had not yet been anticipated. The 100- and 63-foot radius buckets were found to be unnecessarily large for a discharge of 1,010 second-feet per foot of width and a velocity of about 75 feet per second. The 42-foot radius bucket was found to be the smallest bucket which would provide satisfactory performance.

The tail water depth was not sufficient for good performance when the bucket invert was 45 feet below tail water elevation. Performance was better with the invert 69 feet below tail water elevation, but for all invert elevations tested a ground roller occurred which moved bed material from downstream and deposited it against the bucket lip.

The second stage in the development was to modify the bucket to prevent the piling of bed material along the lip. Tubes were placed in the bucket lip through which jets of water flowed to sweep away the loose material. Results were satisfactory at low discharges, but for the higher flows the loose material was piled deeply over the tube exits, virtually closing them.

Slots in the bucket lip were then used instead of larger tubes. The slots were found to not only keep the bucket lip free of loose material, but also provided exits for material that became trapped in the bucket during unsymmetrical operation of the spillway.

In order that the effectiveness of the bucket in dissipating the energy of spillway flows be maintained, the slots were made no larger than necessary to prevent deposition at the bucket lip. The first slots tested were 1 foot 9 inches wide, spaced three times that distance apart. The slot bottoms were sloped upward on an 8° angle so that the emerging flow would not scour the channel bottom, and were made tangent to the bucket radius to prevent discontinuities in the surface over which the flow passed. The spaces between the slots then became known as teeth and were 5 feet 3 inches wide. Three tooth designs, shown in Figure 5, were tested.



SOLID BUCKETS TESTED

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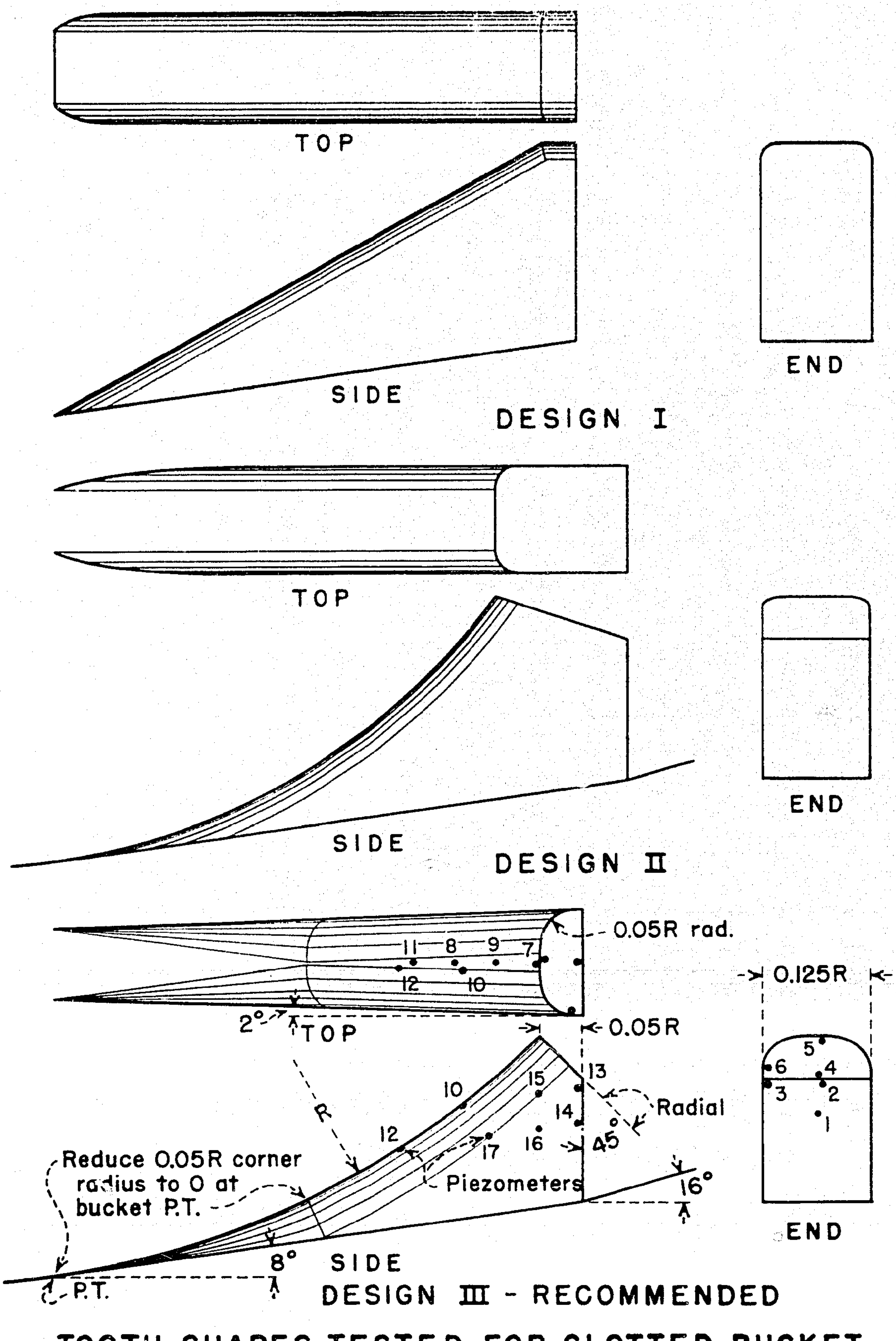
FIGURE 5



TOOTH SHAPES TESTED FOR SLOTTED BUCKET

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Tooth Shape, Spacing, and Pressures

Tests using Tooth Design I were encouraging. The energy dissipating action of the bucket and the elimination of piled material along the bucket lip were both satisfactory. However, small eddies, formed by the jets leaving the slots, lifted loose gravel to produce abrasive action on the downstream face of the teeth. Therefore, a sloping apron was installed downstream from the teeth to help spread the jets from the slots and also to keep loose material away from the teeth. The apron was sloped upward slightly steeper than the slope of the slots, to provide better contact with the jets. The apron was found to perform as intended; however, the best degree of slope for the apron and the shortest possible apron length were not determined until after the tooth design and the tooth spacing were determined.

Pressures observed on Tooth Design I at the piezometer locations shown in Figure 5 were, in general, satisfactory. Undesirable subatmospheric pressures were found on the downstream face, however.

The profile of Tooth Design II, Figure 5, conformed to the radius of the bucket, eliminating the discontinuity in the flow passing over the teeth. Energy was dissipated more readily and a smoother water surface occurred downstream from the bucket. Pressures were subatmospheric at seven locations, the majority of which were located on the downstream face. The necessary rounding of the edges of the teeth was determined by testing model radii ranging from 0.1 to 0.3 inch. The larger radius (12.6 inches prototype) was found to be the most desirable.

Tooth Design III, Figure 5, was shaped to improve pressure conditions on the sides and downstream face of the teeth and the radius for rounding and edges was increased to 15 inches prototype. Subatmospheric pressures still occurred on the downstream face at Piezometers 3, 4, and 5, but the subatmospheric pressures were above the critical cavitation range.

Preliminary tests had shown that pressures on the teeth varied according to the tooth spacing. The most favorable pressures consistent with good bucket performance occurred with Tooth Design III, tooth width 0.125R and spacing 0.05R at the downstream end. Table I shows the pressures in feet of water at the piezometers.

Table I

Pressures on Tooth Design III
0.05R Spacing

Piezometer No.	Pressure ft of water	Piezometer No.	Pressure ft of water
1	+1 to +16	9	+58
2	+5 to +13	10	+42
3	-2 to +15	11	+68
4	-13 to +16	12	+49
5	-9 to +11	13	+11
6	+8 to +16	14	+13
7	+22	15	+21
8	+62	16	+34
		17	+39

Piezometers 1 through 6 showed fluctuations between the limits shown. Piezometers 3, 4, and 5 showed negative or subatmospheric values, but since these piezometers are on the downstream face of the teeth it is unlikely that damage would occur as a result of cavitation. According to the pressure data the teeth are safe against cavitation for velocities up to about 100 feet per second, i.e., velocity computed from the difference between headwater and tail water elevations, and may be safe for even considerably higher velocities.

Reducing the tooth spacing to 0.035R raised the pressures on Piezometers 3, 4, and 5 to positive values. Pressures on the tooth are shown in Table II.

Table II

Pressures on Tooth Design III
0.035R Spacing

Piezometer No.	Pressure ft of water	Piezometer No.	Pressure ft of water
1	+36	9	+62
2	+27	10	+57
3	+30	11	+71
4	+26	12	+63
5	+14	13	+21
6	+27	14	+28
7	+39	15	+40
8	+64	16	+47
		17	+58

With 0.035R spacing the teeth should be safe against cavitation for velocities well over 100 feet per second. However, for small buckets the openings between teeth may be too small for easy construction and the slots may also tend to clog with debris. In other respects the bucket performance with 0.035R tooth spacing is satisfactory.

Apron Downstream from Teeth

The slope and length of the apron downstream from the teeth were the remaining bucket dimensions to be determined. Since the apron served to spread the jets from the slots and also improved the stability of the flow leaving the bucket, it was important that the apron characteristics be investigated.

A 16° upward sloping apron was found to be most satisfactory. With a 12° slope the flow was unstable, intermittently diving from the end of the apron to scour the riverbed. Using a 20° slope the spreading action of the flow was counteracted to some degree by the directional effect of the steep apron.

Two apron lengths, one 10 feet and one 20 feet, were tested to determine the minimum length required for satisfactory operation. The longer apron, 0.5R in length, was found necessary to accomplish the spreading of the jets and produce a uniform flow leaving the apron. The 20-foot apron on a 16° slope was therefore adopted for use.

Slotted Bucket Performance

The slotted bucket, shown in Figure 1, operated well over the entire range of discharge and tail water conditions in the sectional model, scale 1:42. The bucket was then rebuilt to a scale of 1:72 and tested on a wide spillway where end effects on the bucket could also be observed and evaluated.

In the 1:72 model minor changes were made before the bucket was constructed and installed. The bucket radius was changed from 42 feet to an even 40 feet, and the bucket invert was lowered from 69 to 75 feet below maximum tail water elevation. Figure 6 shows the 1:72 model in operation with 2[illegible]7,000 second-feet (1,010 second-feet per foot), erosion after 20 minutes of operation, and erosion after 1-1/2 hours of operation

Performance was excellent in all respects; was better than for any of the solid buckets or other slotted buckets investigated. For all discharges the water surface was smoother and the erosion of the riverbed was less.

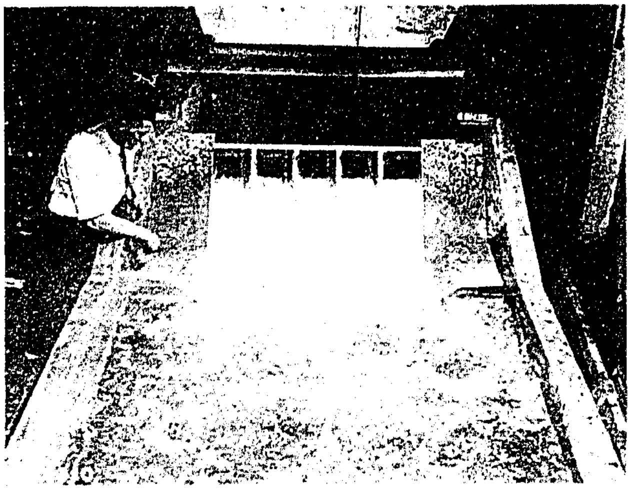
Summary of Slotted Bucket Development Tests

Reviewing the development of the slotted bucket three factors were involved: (1) the radius of the bucket and elevation of the invert with respect to tail water for the given flow conditions; (2) the shaping and spacing of the teeth; and (3) the pitch and length of apron downstream from the teeth. All three factors are important in obtaining the desired energy dissipation, a smooth water surface, and a minimum amount of river channel erosion. Dimensions of the bucket teeth, slots, and apron are expressed in terms of the bucket radius in Figure 1.

GENERALIZATION OF THE SLOTTED BUCKET

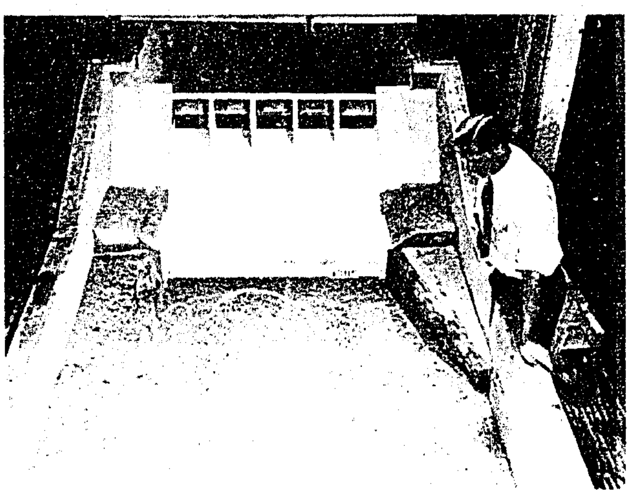
General

The tests made on the Angostura bucket indicated that a satisfactory design could be developed for use at a particular site. It was also evident, however, that generalization of the design would be desirable so that bucket dimensions, proper elevation of bucket with respect to tail water elevation, and the capacity of the bucket could be determined for any installation.



Maximum discharge
1010 second feet
per foot of width

Erosion after
20 minutes



Erosion after
90 minutes

Erosion Test on Angostura Dam Spillway
1:72 Scale Model
Recommended Slotted Bucket

The general features of the bucket, shown in Figure 1, were believed to be satisfactory but before starting the generalization tests possible further improvements in the bucket teeth were investigated. When it was found that the tooth size developed for the Angostura bucket provided best hydraulic performance, tests were then directed toward generalization of the design.

Test Equipment

An entirely new sectional model was constructed and tested in Flume B, Figure 1 of Progress Report II, and also shown in Figure 7 of this report. The flume was 43 feet 6 inches long and 24 inches wide. The head bay is 14 feet deep while the tail bay is 6 feet 3 inches deep and has a 4- by 13-foot glass window on one side. The discharge end of the flume was equipped with a motor driven tailgate, geared to slowly raise or lower the tail water so that continuous observations could be made.

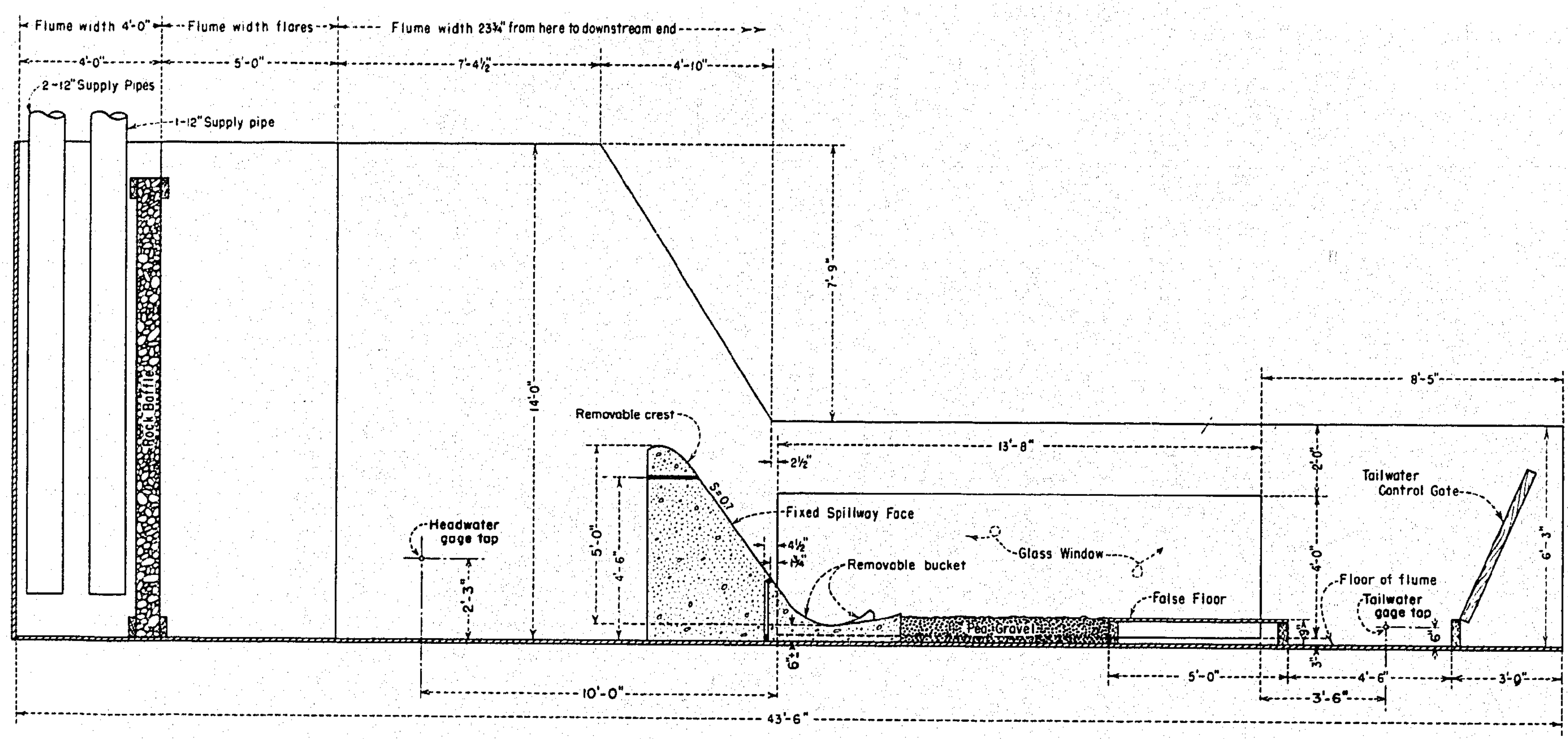
The sectional spillway model was constructed to completely fill the flume width, 24 inches, with an ogee crest at the top of a 0.7 sloping spillway face. The bucket assembly was made easily detachable from the spillway face. Four interchangeable buckets having radii of 6, 9, 12, and 18 inches, constructed according to the dimension ratios shown in Figure 1, were designed so that they could be installed with the buckets inverts located 5 feet below the spillway crest and about 6 inches above the floor of the flume. All flow surfaces were constructed of galvanized sheet metal with smooth joints. The downstream channel was a movable bed molded in pea gravel. The gravel analysis:

Retained on 3/4-inch screen	6 percent
Retained on 3/8-inch screen	66 percent
Retained on No. 4 screen	25 percent
Retained on Pan	3 percent

Flow was supplied to the test flume through a 12-inch centrifugal pump and was measured by one of a bank of Venturi meters permanently installed in the laboratory. Additional water, beyond the capacity of the 12-inch pump, was supplied by two vertical-type portable pumps equipped with two portable 8-inch orifice-Venturi meters. All Venturi meters were calibrated in the laboratory. Water surface elevations were measured with hook gages mounted in transparent plastic wells.

Bucket Modifications Tested

General. To determine whether practical modifications could be made to improve the performance of the Angostura slotted bucket the 12-inch radius bucket, constructed according to the recommended



SECTION ON ℄ OF TEST FLUME

TEST FLUME AND SECTIONAL SPILLWAY

FIGURE 7

dimensions in Figure 1, was first tested. The purpose in repeating the test was to obtain data for generalization and to establish a performance standard with which to compare the modified buckets, all to be made on the 12-inch radius bucket.

To provide a standard bucket test, which was necessary to reduce the amount of testing required on each bucket modification, the 12-inch Angostura bucket was thoroughly investigated. The bucket capacity was estimated to be about 6 second-feet. Best performance for this flow occurred with the tail water 2.3 feet above the bucket invert, Figure 2B. These conditions were used for the standard bucket test. Also, as part of the standard test the movable bed was molded level, just below the bucket lip, at the start of a test.

In retesting the Angostura bucket it was noted that much of the energy dissipation occurred as a result of the spreading action downstream rather than in the rolling action in the bucket. Flow passed through and over the teeth to emerge at the water surface some 3 or 4 feet downstream from the bucket, Figure 2B, producing a boil at this point and waves on the water surface downstream. In some installations action of this type might be objectionable since bank erosion could occur or powerhouse operation could be affected.

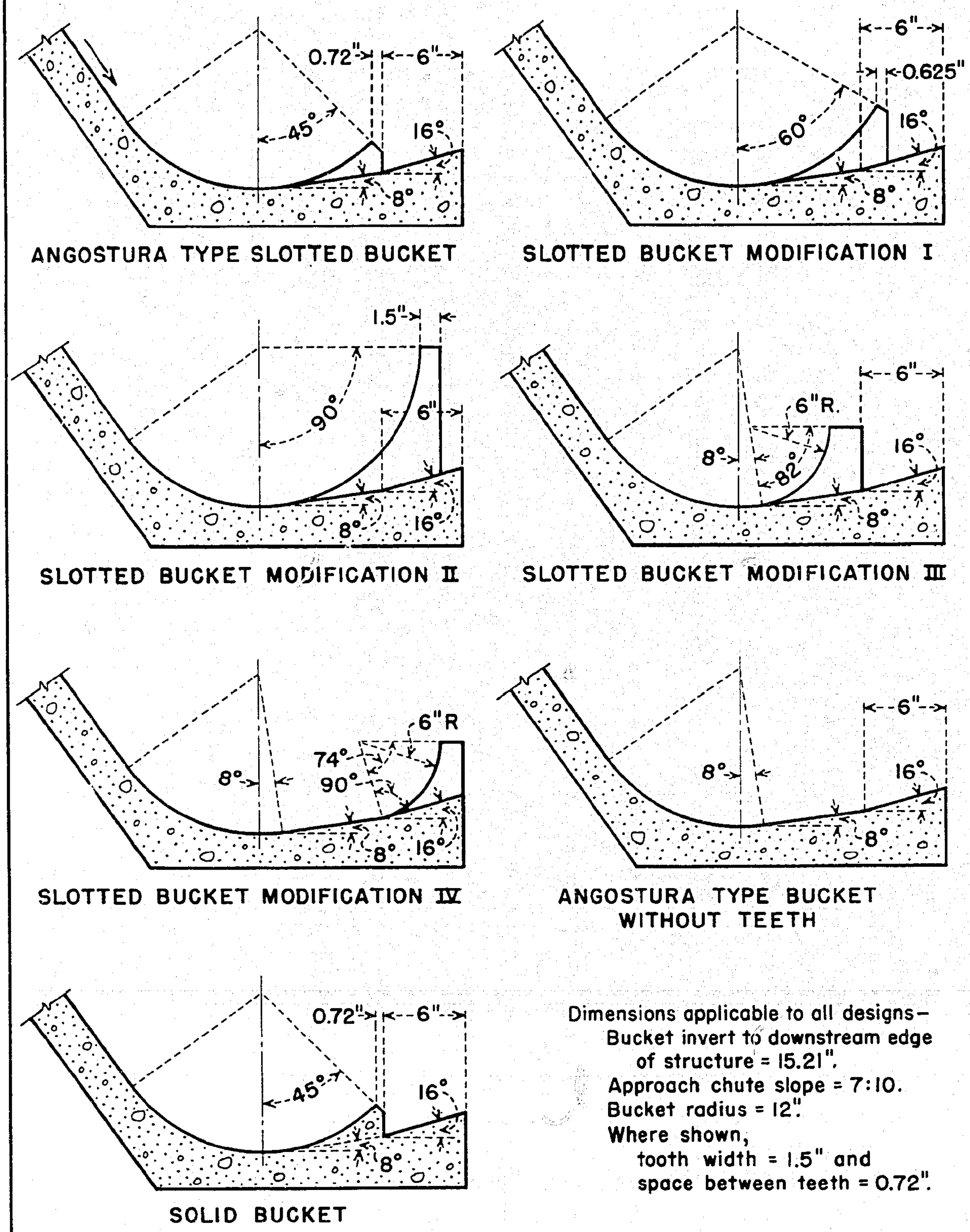
It was concluded from these tests that if improvements could be made in the bucket performance, reduction in wave action in the downstream channel should be given first consideration since energy dissipation and bed erosion were entirely satisfactory. Four modifications of the bucket teeth were tested; the bucket with teeth removed was also investigated. Also, a solid bucket was tested to indicate the relative advantages of the two types. Only a brief description of these tests is given since none of the modifications are recommended for general use. However, to indicate the scope of the testing a summary of these tests is given.

<u>Tooth Modification I</u>. In the first modification the teeth were extended in height from 45° to 60° as shown in Figure 8. The spacing of the teeth and the shape and length of the apron were not modified since these had been carefully determined in the early development tests.

In operation with the standard test the bucket performed much the same as the original. The boil occurred about 6 inches farther upstream and was higher than for the Angostura bucket. Waves were also as high or higher, and since the sweepout point was about the same no further testing was done.

<u>Tooth Modification II</u>. In both the Angostura and modified buckets tested it was noted that the water surface directly over the

FIGURE 8



SLOTTED BUCKET MODIFICATIONS TESTED

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bucket was lower than the tail water downstream. It was believed desirable to move the boil upstream directly over the bucket, consequently, the teeth were extended in height to an angle of 90°, as shown in Figure 8. It was realized that the teeth would be too tall to be structurally stable in any but a small bucket but the trend in performance was the real purpose in making the test.

Performance of this modified bucket was excellent for the standard test. A large portion of the flow was turned directly upward to the water surface where it rolled back into the bucket. The tail water depth directly over the bucket invert was about the same as the depth downstream. A slight boil could be detected over the teeth, but it was not nearly as great as for the two previous slotted buckets tested. The flow passing between the teeth also provided fairly uniform distribution of velocity from the channel bed to the water surface in the channel downstream. The water surface was quite smooth and the channel bed was not disturbed.

The bucket also performed well for high and low tail water elevations. The tail water could be raised to a higher elevation than for the two previous buckets before the flow pattern changed to scour the channel bed; and it could be lowered to a lower elevation before the flow was swept from bucket. Thus, the range of tail water depths for which the bucket operated satisfactorily was increased.

The performance of this bucket was very good in every respect; however, cavitation could occur more readily on the surfaces of the tall teeth. Cavitation pressures or the possibility of eliminating such pressures were not investigated because the teeth were considered too high for practical use on large structures. Therefore, this slotted bucket modification is suggested for possible use with small buckets where cavitation pressures cannot occur, i.e., velocities near the teeth below 50 feet per second.

Tooth Modification III. In the third modification a tooth radius half that of the bucket radius was used, as shown in Figure 8, to curve the teeth to a height of 90°. This modification was made to determine whether the height of the teeth, or the 90° curvature of the teeth, provided the improved performance.

Tests showed that the shorter teeth were not effective in lifting flow to the surface. Flow passed over and through the teeth to form a high boil downstream similar to the first modification. In addition, observation of the flow passing over the tops of the teeth indicated that cavitation pressures were a likely possibility. Pressures were not investigated since performance was not as good as for the Angostura slotted bucket.

Tooth Modification IV. Modification IV utilized the same tooth as Modification III, but the teeth were placed on the apron at the downstream end of the bucket, as shown in Figure 8. It was anticipated that the teeth, placed farther downstream and at a slightly higher elevation, would turn a portion of the flow directly upward to the water surface as for Modification II. Performance tests showed that the teeth turned more of the flow upward but the performance was no better than for the Angostura design.

Angostura bucket with teeth removed. The Angostura bucket without teeth is shown in Figure 8. This design was not expected to perform as well as the slotted Angostura bucket, but was tested to indicate the value of the teeth and slots in dissipating the energy of the spillway flow. Operation was quite satisfactory for flows of 3 and 4 second-feet but performance was poor for 6 second-feet. For the higher flows of 5 to 6 second-feet the flow leaving the bucket was unstable and the water surface was rough. For a few seconds the boil would be quite high then suddenly would become quite low. Erosion of the riverbed was negligible for all flows, however.

The tests without teeth in the bucket indicated that the primary function of the teeth is to stabilize the flow and reduce water surface fluctuations in the channel downstream. The tests also suggested the fact that should the teeth in the Angostura bucket deteriorate over a period of time in a prototype structure, the ill effects of the deterioration could be easily observed and evaluated. Discharges up to about half maximum would be satisfactory with the teeth gone.

Solid bucket. The solid bucket design, shown in Figure 8, was tested to compare the action with that of a slotted bucket. Figure 2 shows the bucket performing under similar discharges and tail water elevations. For the solid bucket, all of the flow is directed to the water surface a short distance downstream from the bucket, resulting in a very high boil. Part of the flow rolls back into the bucket while part continues on downstream. Since there are no slots to provide flow currents in a downstream direction under the boil, a violent undercurrent flowing upstream, or ground roller, exists at all times. It is the ground roller that moves gravel upstream and deposits it at the bucket lip. Currents passing over the lip then pick up the material and move it downstream, resulting in a continual circulation of bed material. The action itself is harmless except that the lip is exposed to abrasive action and with unsymmetrical operation of the spillway gates the material is often swept into the bucket. Once the material is in the bucket, it is trapped and causes erosion of the concrete surfaces as it is moved about both laterally and longitudinally inside the bucket arc. Therefore, a solid bucket, without slots, has certain disadvantages where loose material may be carried into the bucket or where the high boil might be objectionable.

Some advantages, however, were found for use of a solid bucket. A lower tail water elevation is required to sweep the flow out of the bucket and the flow could not be made to dive from the bucket lip to scour the channel bed. However, in general, the slotted bucket performed better than the solid bucket.

Summary

The Angostura bucket performed better than any of the modified forms of the bucket except Tooth Modification II. However, the high teeth in Modification II were considered to be impractical for most prototype construction and the possibility of cavitation at high velocities is great. For small structures the relatively high teeth might be practical in which case the use of Tooth Modification II should be considered.

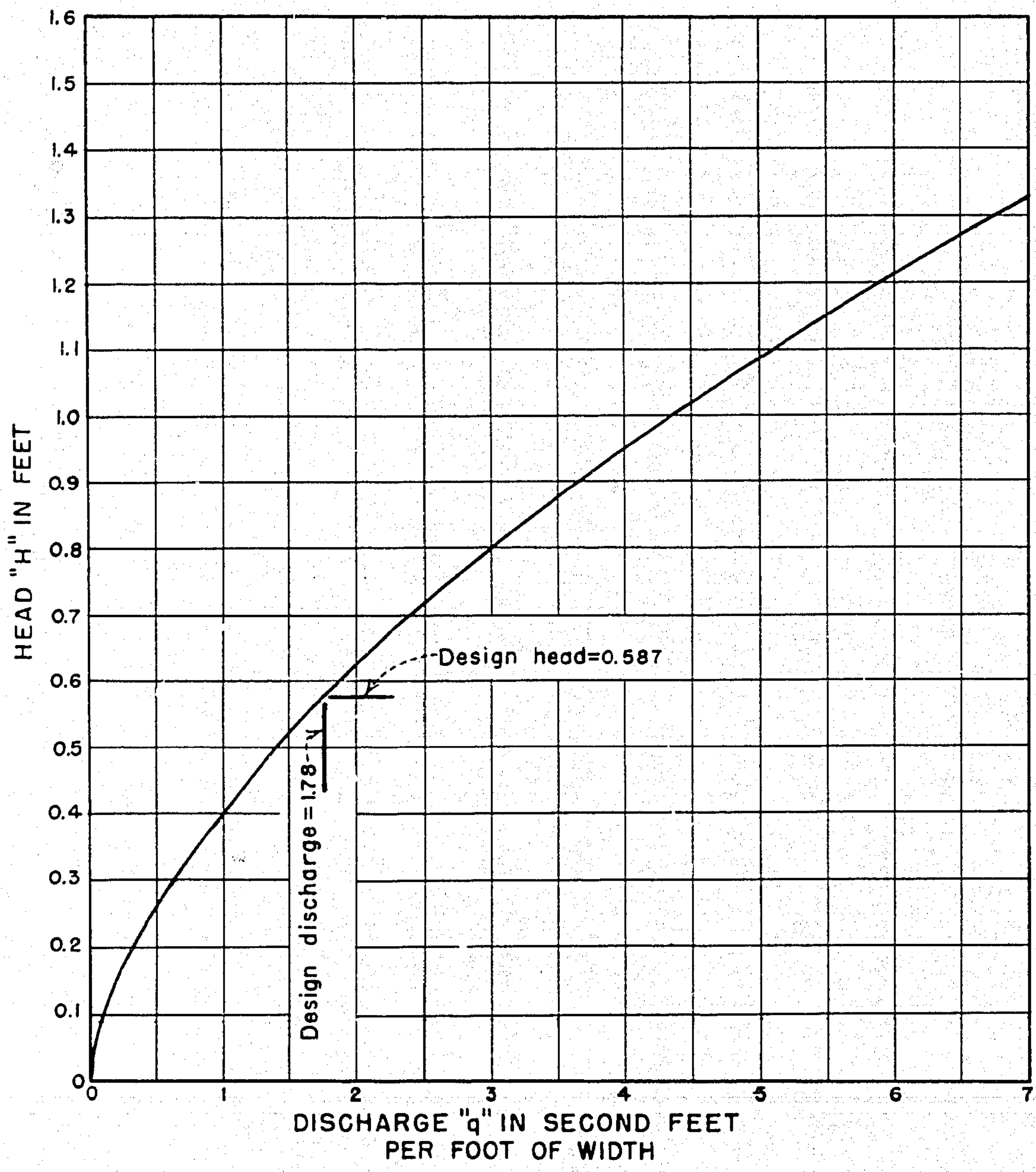
The Angostura slotted bucket with or without modifications, in general, is considered to be superior in performance to the solid bucket. The Angostura slotted bucket also provides more stable flow and better energy dissipation than did the Angostura bucket with teeth removed; however, with the teeth removed fairly good energy dissipation occurred without disturbing the channel bed. The Angostura slotted bucket without modification is, therefore, recommended for use on spillway structures where tail water depths are within the limits required for use of a bucket type energy dissipator.

Determination of Radius and Tail Water Limits

General

The investigation to determine the minimum bucket size and tail water limits for a range of structure sizes, discharges, and overfall height was accomplished with the testing of 6-, 9-, 12-, and 18-inch radius buckets, tested in that order.

For each bucket installation, a range of discharges was passed over the spillway. The head on the spillway was measured and recorded. The relation between head and discharge on the spillway is shown in Figure 9. For each discharge, the tail water depth was lowered slowly until the flow swept out of the bucket, as shown in Figure 10. Since the bucket study did not include flip-type buckets, the depth at sweepout was considered too low for proper performance of the bucket. The tail water sweepout depth, measured above the bucket invert, was recorded in Tables III to VI and plotted in Figure 11. Figure 10 also shows the bucket operating with tail water depth just safely above the depth required for



DISCHARGE CALIBRATION OF
THE 5-FOOT MODEL SPILLWAY

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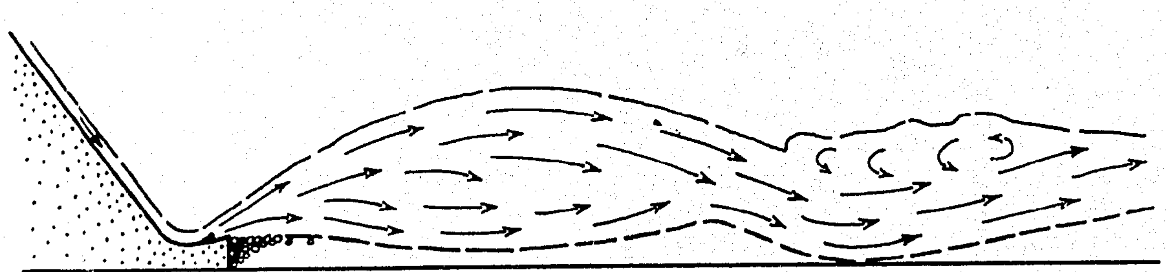
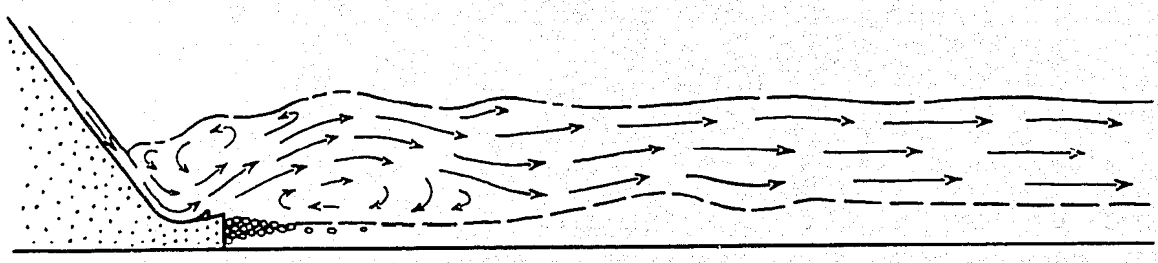
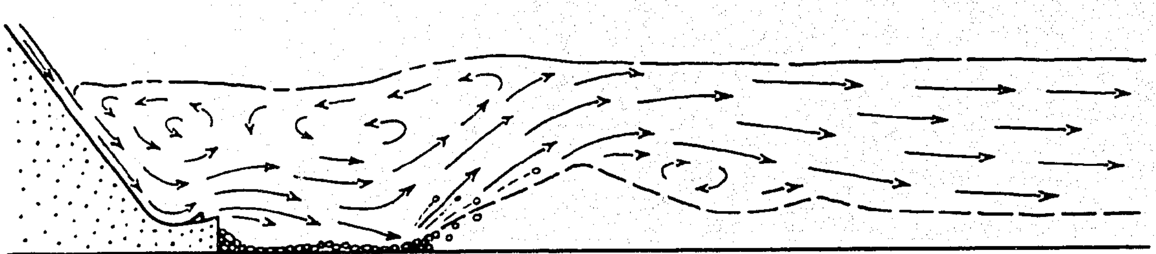
FIGURE 10.



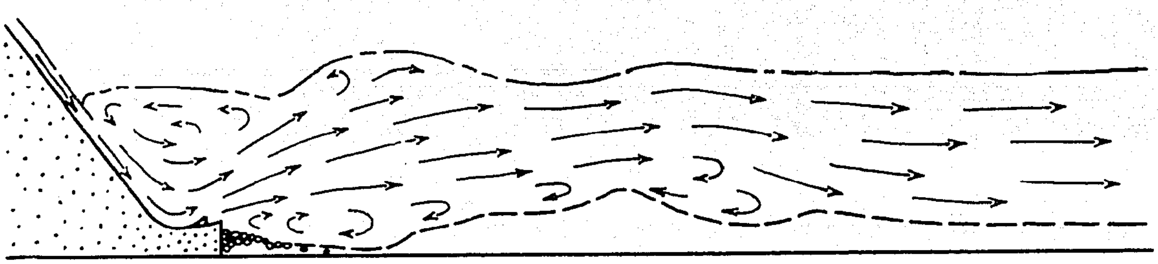
A. Tailwater below minimum. Flow sweeps out.



B. Tailwater below average but above minimum. Within normal operating range.



C. Tailwater above maximum. Flow diving from apron scours channel



D. Tailwater same as in C. Diving jet is lifted by ground roller. Scour hole backfills similar to B. Cycle repeats.

(Bed level 0.3-inch below apron lip at start of test)

6-INCH BUCKET - DISCHARGE (q) = 1.75 C.F.S.

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Table III

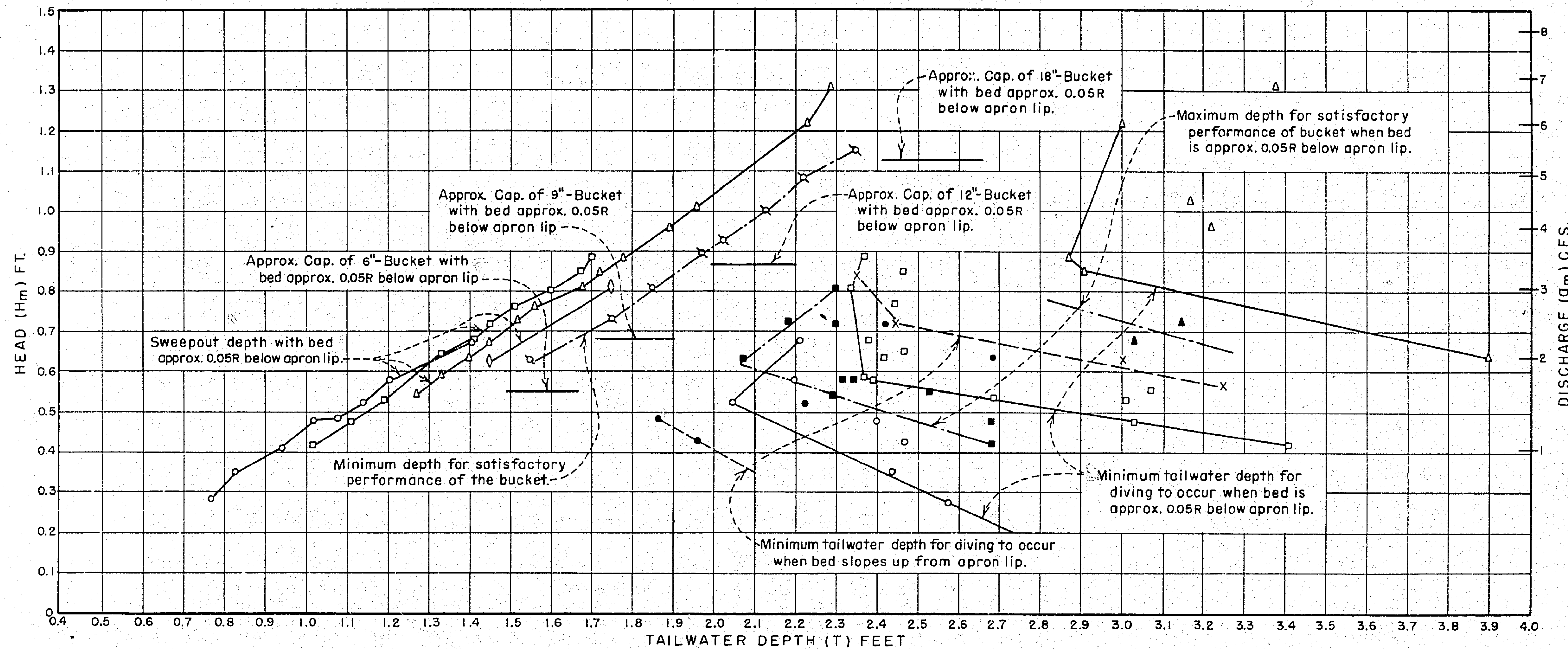
DATA AND CALCULATED VALUES FOR 6-INCH RADIUS BUCKET

		Bed was approximately 0.05R below apron lip at beginning of each run								
		1	2	3	4	5	6	7	8	9
						Sweepout Conditions				
1	H	0.198	0.274	0.352	0.413	0.480	0.481	0.526	0.581	0.678
2	T (sweepout depth)	0.767	0.765	0.826	0.943	1.023	1.081	1.139	1.203	1.403
3	q	0.31	0.54	0.81	1.03	1.30	1.30	1.50	1.75	2.25
4	T_{min}	0.967	0.965	1.026	1.143	1.223	1.281	1.339	1.403	1.603
5	$\frac{V_1^2}{2g} = X + H - T_{min}$	4.231	4.309	4.326	4.270	4.257	4.200	4.187	4.178	4.075
6	V_1	16.50	16.65	16.70	16.58	16.56	16.45	16.42	16.41	16.20
7	D_1	0.019	0.032	0.048	0.062	0.078	0.079	0.091	0.107	0.139
8	$F = \frac{V_1}{\sqrt{gD_1}}$	21.2	16.31	13.36	11.72	10.42	10.31	9.50	8.85	7.65
9	$\frac{T_{min}}{D_1}$	51.43	29.78	21.10	18.40	15.57	16.21	14.66	13.16	11.54
10	$D_1 + \frac{V_1^2}{2g}$	4.245	4.341	4.374	4.332	4.335	4.279	4.278	4.285	4.214
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
						Diving Flow Conditions				
12	T (diving depth)	2.565	2.576	2.435	2.464	2.439	2.397	2.043	2.200	2.213
13	T_{max}	2.065	2.076	1.935	1.964	1.939	1.897	1.543	1.700	1.713
14	$\frac{V_1^2}{2g} = X + H - T_{max}$	2.133	2.198	2.417	2.449	2.541	2.584	2.983	2.881	2.965
15	V_1	11.72	11.89	12.47	12.55	12.78	12.90	13.86	13.62	13.81
16	D_1	0.026	0.045	0.065	0.089	0.102	0.101	0.108	0.128	0.163
17	$F = \frac{V_1}{\sqrt{gD_1}}$	12.67	9.84	8.62	7.40	7.06	7.20	7.42	6.70	6.02
18	$\frac{T_{max}}{D_1}$	77.92	45.72	29.76	21.62	19.06	18.82	14.26	13.23	10.51
19	$D_1 + \frac{V_1^2}{2g}$	2.159	2.243	2.486	2.538	2.643	2.685	2.983	3.009	3.128
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.23	0.22	0.20	0.20	0.19	0.19	0.17	0.17	0.16

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweepout depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Maximum capacity of bucket estimated to be 1.5 to 1.75 second-feet per foot of width.

FIGURE 11



BUCKET RADIUS (R) INCHES	BUCKET CAPACITY IN C.F.S. PER FT. OF WIDTH	
	BED APPROX. 0.05R BELOW APRON LIP	BED SLOPES UP FROM APRON LIP
6	1.5 TO 1.75	—
9	2.0 TO 2.5	1.5
12	3.25 TO 3.5	2.0 TO 2.5
18	5.0 TO 5.5	—

TABLE NO	TEST DATA SYMBOLS	BUCKET RADIUS (R) INCHES	BED ARRANGEMENT	DESCRIPTION OF TEST DATA SYMBOLS
III	○	6	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured
IV	□	9	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured
V	△	12	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured.
VI	◊	18	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth
	¤	18	Bed approx. 0.05R below apron lip.	Est. Min. tailwater depth for satisfactory performance of the bucket.
	■	9	Bed approx. 0.05R below apron lip.	Est. Max. tailwater depth for satisfactory performance of the bucket.
	▲	12	Bed approx. 0.05R below apron lip.	Est. Max. tailwater depth for satisfactory performance of the bucket.
IV	●	9	Bed sloped up from apron lip.	Min. tailwater depth at which diving occured.
V	x	12	Bed sloped up from apron lip.	Min. tailwater depth at which diving occured.

TAILWATER LIMITS AND BUCKET CAPACITIES

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sweepout. The tail water depth just safely above the depth required for the sweepout will, henceforth in this report, be called the lower or minimum tail water limit.

For each discharge the upper tail water limit was also investigated. The tail water was raised slowly until the flow dived from the apron lip, as shown in Figures 3 and 10c. When diving occurred a deep hole was scoured in the channel bed near the bucket. The tail water depth for diving, considered to be too high for proper performance of the bucket, was also recorded in Table III and plotted in Figure 11. The tail water depth that is just safely below the depth required for diving will, henceforth, be called the upper or maximum tail water limit.

Six-inch Radius Bucket

Lower tail water limit. At the sweepout depth, the flow left the bucket in the form of a jet, Figure 10. The movable bed was quiet and undisturbed from the bucket downstream to the point where the jet landed. The jet scoured the channel bed only at the point of contact, and did not cause excessive water surface roughness downstream. A more undesirable flow pattern occurs just before sweepout, however, when an unstable condition developed in the bucket and in the channel causing excessive erosion and water surface roughness. It is this transition region which makes it undesirable to design a bucket for both submerged and flip action.

At the lower tail water limit, i.e., just above sweepout, the gravel in the movable bed began to move. The gravel was not carried away from the bucket, but instead was lifted and dropped by numerous small eddies that formed in the water between the main flow leaving the bucket and the movable bed. The action was not considered desirable nor particularly objectionable.

The lower tail water limit appeared to be from 0.05 to 0.15 of a foot above the sweepout depth. Only the sweepout depth was recorded in the data shown in Table III since it was a more definite point than the minimum low tail water limit. A safe lower limit was established at the conclusion of all model testing by adding 0.2 of a foot to the sweepout tail water depth.

Upper tail water limit. At the tail water depth required for diving to occur, it was noted that after 3 or 4 minutes in the model the diving flow suddenly ceased and the flow rose to the surface as shown in Figure 10. The changeover occurred only after the movable bed became sufficiently scoured to allow the ground roller to form and lift the flow from the apron lip to the water surface. The ground roller then moved the pea gravel deposit upstream into the scoured hole until the riverbed became nearly level with the apron lip. At the same time, the strength of the undercurrent was reduced until it was no longer capable of lifting the flow to the water surface and the flow dived again to start another cycle which was repeated over and over. Very little bed material was moved downstream out of reach of the ground roller even after several cycles. Five or six minutes were required for one cycle.

When the flow was diving, the water surface was very smooth; but, when the flow was directed toward the surface a boil formed and a rough downstream water surface was in evidence. In the former case, part of the energy was dissipated on the channel bed, while in the latter case, energy was dissipated on the surface.

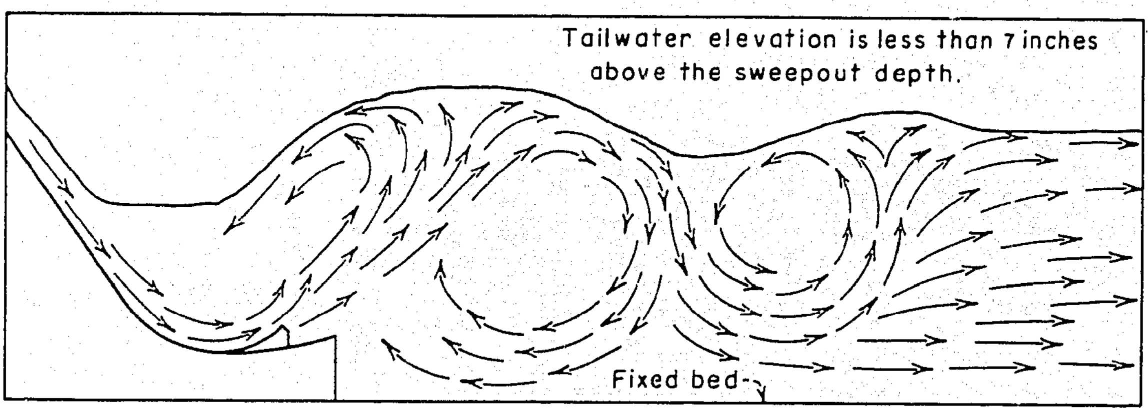
Near the upper tail water limit, diving occurred in spurts not sufficiently long to move bed material. As the depth approached that required for sustained periods of diving, the momentary spurts occurred more often. In the test data recorded in Table III and plotted in Figure 11, the upper limit was not recorded; instead, the tail water depth that caused sustained diving was recorded because it was a more definite point. At the conclusion of all model testing, the upper tail water limit was established by subtracting 0.5 foot from the tail water depth at which sustained diving occurred. This margin of safety was sufficient to prevent momentary diving in all cases.

The first tests showed that it was difficult to get consistent results for the tail water depth at which diving occurred. It was determined that the upper tail water limit was dependent also upon the shape characteristics of the channel bed, especially its elevation downstream from the bucket. Since with a movable bed it was difficult to maintain the same channel bed characteristics between one test run and another, the gravel was removed from the model completely in anticipation that the upper tail water limit could be determined by merely observing the flow pattern.

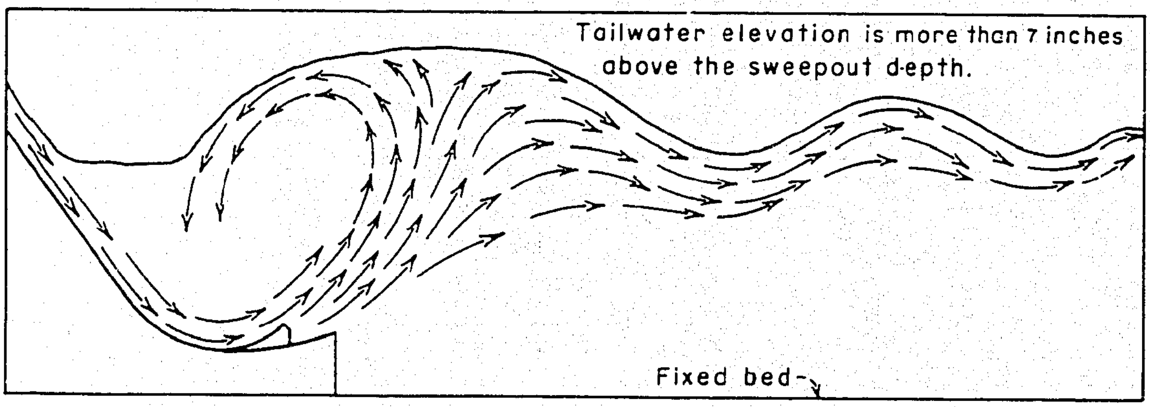
The gravel was removed completely so that the floor of the model, which was 6 inches below the bucket invert, was the channel bed. With this arrangement there was no upper limit since the flow could not be made to dive from the end of the bucket for any tail water elevation, Figure 12.

It was then decided to try a solid wood floor at the elevation of the apron lip to represent the channel bed. For this arrangement flow from the bucket followed along the solid bed then rose to the surface downstream, as shown in Figure 12. For the higher tail water elevations the flow followed along the solid floor for a greater distance before

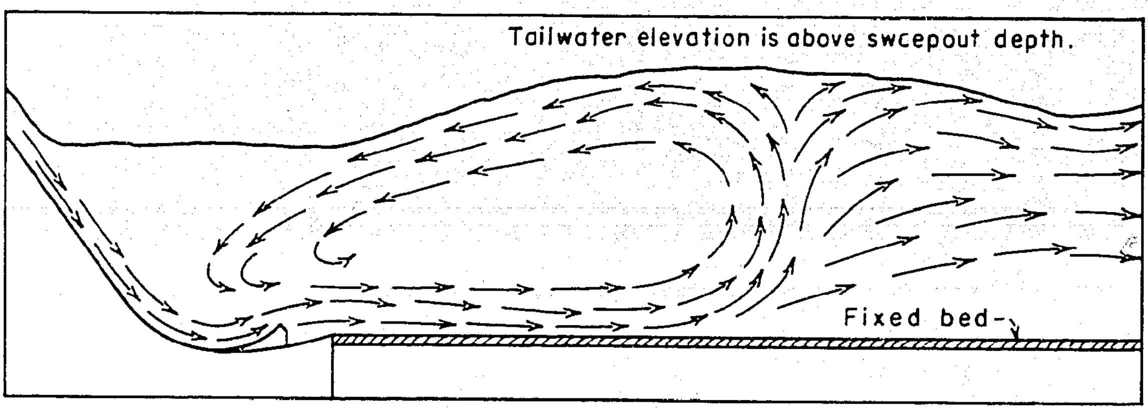
FIGURE 12



A. FIXED BED 6 INCHES BELOW BUCKET INVERT. DESIRABLE TAILWATER DEPTH



B. FIXED BED 6 INCHES BELOW BUCKET INVERT. LESS DESIRABLE TAILWATER DEPTH



C. FIXED BED AT APRON LIP LEVEL

Note:
Bucket radius is 6 inches.
Discharge is 1.75 second feet per unit foot of width.

FLOW CURRENTS FOR VARIOUS ARRANGEMENTS OF FIXED BEDS

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turning upward. Since no other changes in flow pattern were apparent at high tail water elevations, again no upper limit could be found.

Testing was continued using the pea gravel movable bed, molded level just below the apron lip. It was necessary to reshape the gravel bed before each test to obtain consistent upper limit results; even then it was difficult. Testing showed that it was important that the channel bed be slightly below the apron lip elevation. If the movable bed was at lip elevation, the diving flow pattern occurred at a much lower tail water elevation. Therefore, the bed was maintained at approximately 0.05R, or 0.3 of an inch, below the apron lip of the bucket at the beginning of each test.

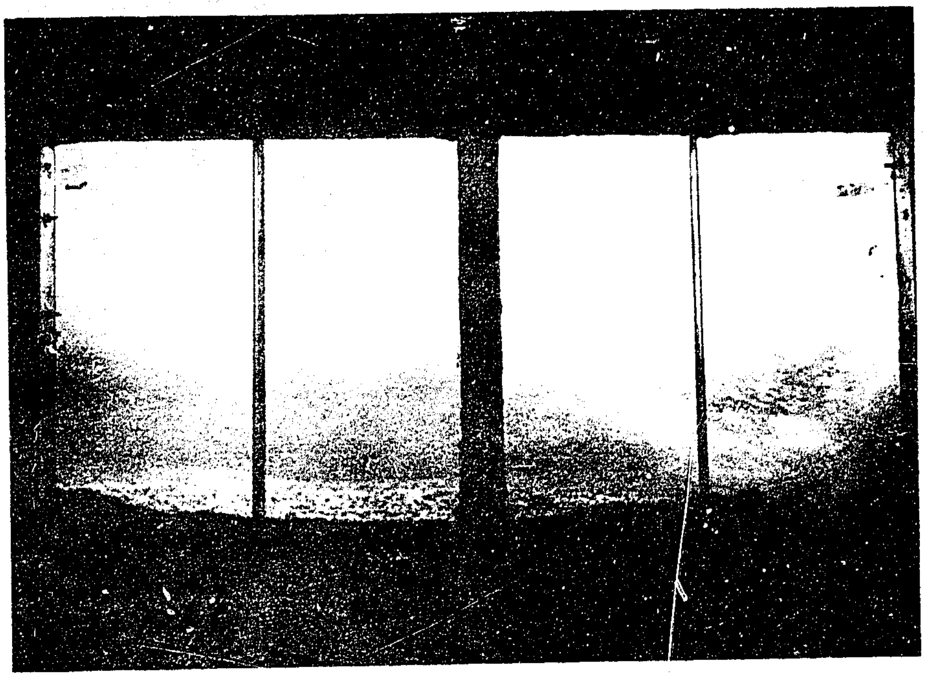
Maximum capacity. As the discharge was increased and the capacity of the bucket was approached, the difference between the upper and lower tail water limits became smaller. The maximum capacity of the bucket was judged by the general performance and by the range of useful tail water elevations between the upper and lower tail water limits, Figure 11. The maximum capacity of the 6-inch bucket was judged to be 3 to 3.5 second-feet or 1.5 to 1.75 second-feet per foot of bucket width. The performance of the bucket for 3.5 second-feet of flow with a normal tail water elevation is shown in Figure 10. The water surface is somewhat rough at this discharge.

Data were not obtained for other movable bed arrangements with the 6-inch bucket. In testing the larger radius buckets, however, it was decided to include a sloping bed arrangement in the investigation.

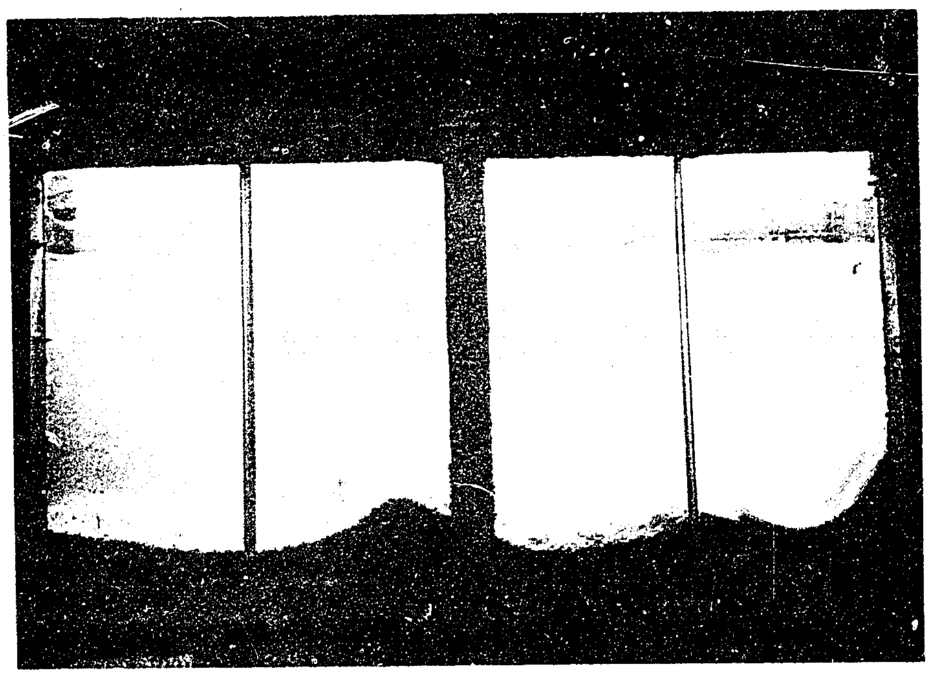
Nine-inch Radius Bucket

The 9-inch bucket was tested in the same manner as the 6-inch bucket. The bucket in operation, just before diving and after diving occurred, is shown in Figure 13. Judged by the difference between the upper and lower tail water limits and by the general performance, the maximum capacity of the 9-inch bucket was determined to be between 4 and 5 second-feet, or 2 to 2.5 second-feet per foot of width. Discharges of 3, 4, 5, and 6 second-feet with a normal tail water depth of 1.85 feet are shown in Figure 14. For 6 second-feet the tail water range for satisfactory performance was quite narrow since a depth of 1.65 feet was too low and 2.3 feet was too high.

Water surface roughness for the maximum discharge of the 9-inch bucket was greater than for the maximum discharge of the 6-inch bucket. To aid in defining the surface conditions, measurements were made for a range of flows with the tail water about halfway between the upper and lower limits, Figure 15.



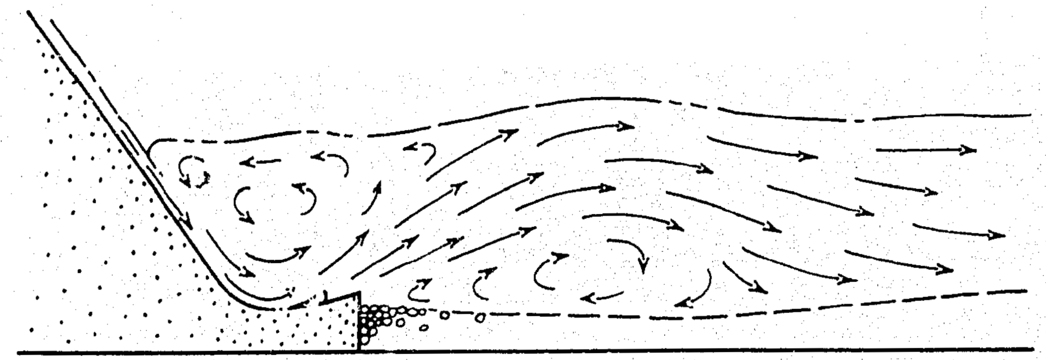
A. Flow is about to dive from apron lip--maximum tailwater depth limit has been reached.



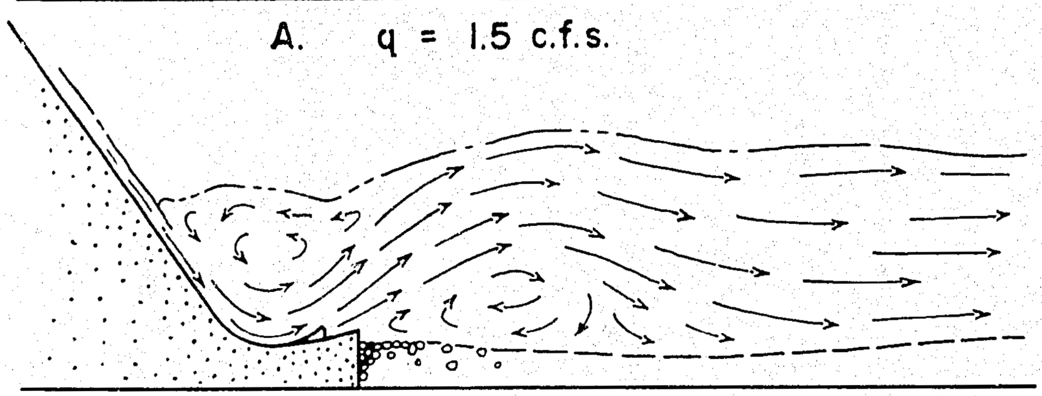
B. Flow is diving from the apron lip--maximum tailwater depth limit has been exceeded.

Nine-Inch Bucket--Discharge (q) = 1.5 c.f.s.

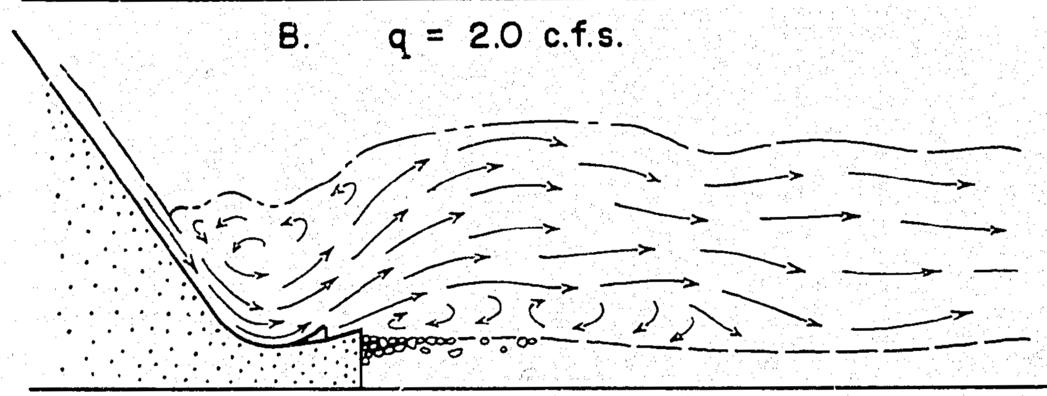
FIGURE 14



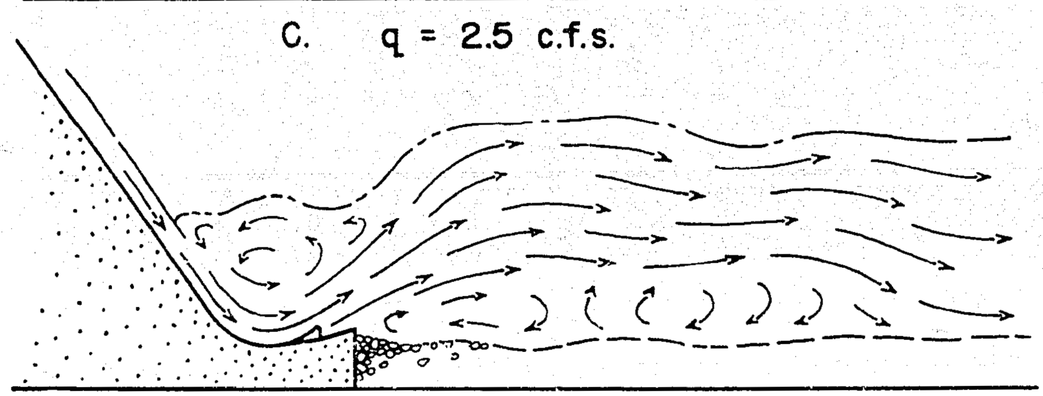
A. q = 1.5 c.f.s.



B. q = 2.0 c.f.s.



C. q = 2.5 c.f.s.



D. q = 3.0 c.f.s.

(Bed level 0.5-inch below apron lip at start of test.)

9-INCH BUCKET — TAILWATER DEPTH = 1.85 FEET

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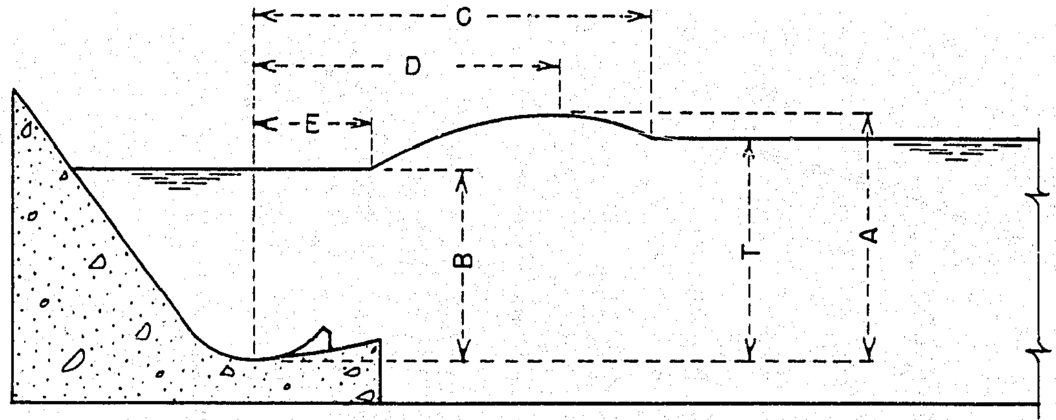
FIGURE 15



9-INCH BUCKET

Q-cfs	q-cfs	T-ft.	A	B	C	D	E
3.0	1.50	1.85	25	19	45	25	5
3.0	1.50	2.40	32	26	46	27	1
3.50	1.75	1.85	26	19	45	25	5
4.00	2.00	1.85	27	19	45	25	5
4.50	2.25	1.85	28	19	48	28	6
5.00	2.50	1.85	28	18	50	32	6
5.50	2.75	1.85	29	17	51	31	6
6.00	3.00	1.85	30	16	52	32	6

12-INCH BUCKET

Q-cfs	q-cfs	T-ft.	A	B	C	D	E
5.0	2.5	1.65	32	23	52	35	14
6.0	3.0	1.65	33	22	62	37	11
7.0	3.5	1.65	33	21	68	37	9
8.0	4.0	1.65	35	19	70	37	6
12.0	6.0	—	36	7	90	40	1

NOTE: Dimensions A, B, C, D, and E are in inches

AVERAGE WATER SURFACE MEASUREMENTS

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The tail water sweepout depth and the depth at which diving occurred are recorded in Table IV and plotted in Figure 11 for a range of flows tested with bed elevation approximately 0.05R, or 0.5 inch, below the apron lip. For a given discharge the tail water sweepout depth was not as low as for the 6-inch bucket but the diving depth was higher.

The upper tail water limit was again difficult to determine since diving occurred over a range of tail water. However, a reasonably safe upper limit appeared to be approximately 0.5 of a foot below the average depth for diving to occur. The minimum safe limit appeared to be from 0.05 to 0.15 of a foot above the sweepout depth.

Upper and lower tail water limits were also determined with the channel bed sloping 16° upward from the apron lip to approximately 6 inches above the lip, since this type of installation will occur frequently in many installations. Tests on this arrangement showed that sweepout occurred at the same depth but diving occurred with a much lower tail water depth. Diving occurred at about the same tail water depth as for the 6-inch bucket with the level bed just below the lip. The maximum capacity of the bucket did not change with bed arrangement. Thus, the performance with the sloping bed was nearly identical to the performance with the level bed except that the operating range between minimum and maximum tail water depth limits was greatly reduced because of the lower elevation at which diving occurred.

Twelve-inch Radius Bucket

The performance characteristics of the 12-inch bucket were similar to those of the 6- and 9-inch buckets. Figure 16 shows the performance for flows ranging from 5 to 8 second-feet with normal tail water depth of 2.3 feet. Surface waves were greater than for the 6- and 9-inch buckets; Figure 15 may be used to compare the surface characteristics for the 9- and 12-inch buckets. The maximum capacity of the bucket was estimated to be from 6.5 to 7 second-feet, or 3.25 to 3.5 second-feet per foot of width.

Tail water depths for sweepout and diving with the bed level approximately 0.05R, or 0.6 of an inch, below the apron lip are recorded in Table V and plotted in Figure 11. Again, as with the smaller buckets, it was difficult to get consistent data for the diving jet and to determine the exact margin of safety required for establishing the upper and lower tail water depth limits. However, the safe margins appeared to be about the same as for the smaller buckets previously tested.

The tests were repeated with the bed sloping upward at 16° to about 6 inches above the lip; again, the results were comparable to those

Table IV

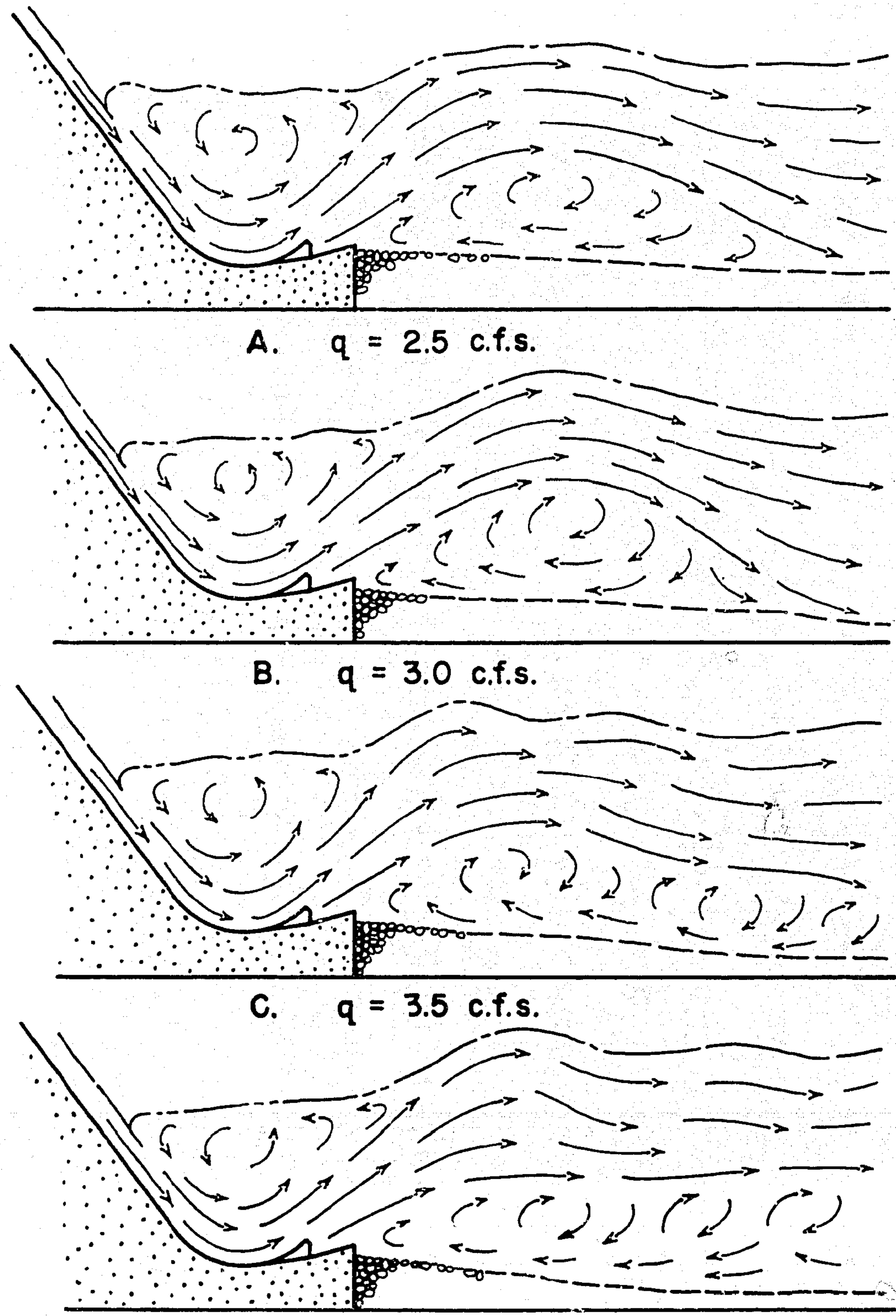
DATA AND CALCULATED VALUES FOR 9-INCH RADIUS BUCKET

	Run No.	Bed was approximately 0.05R below apron lip at beginning of each run															Bed slopes up from apron lip				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Sweepout Conditions																			
1	H	0.419	0.476	0.531	0.642	0.682	0.722	0.764	0.805	0.852	0.884	0.534	0.578	0.565	0.633	0.54	0.433	0.435	0.527	0.634	0.723
2	T (sweepout depth)	1.02	1.11	1.19	1.33	1.41	1.45	1.51	1.60	1.67	1.70										
3	q	1.05	1.28	1.52	2.05	2.28	2.50	2.74	3.00	3.30	3.52	1.53	1.73	1.78	2.02	1.56	1.12	1.32	1.50	2.01	2.50
4	T_{min}	1.22	1.31	1.39	1.53	1.61	1.65	1.71	1.80	1.87	1.90										
5	$\frac{V_1^2}{2g} = X + H - T_{min}$	4.199	4.166	4.141	4.112	4.072	4.072	4.054	4.005	3.982	3.984										
6	V_1	16.45	16.38	16.33	16.28	16.20	16.20	15.16	16.06	16.02	16.02										
7	D_1	0.064	0.078	0.093	0.126	0.141	0.154	0.170	0.187	0.206	0.220										
8	$F = \frac{V_1}{\sqrt{gD_1}}$	11.49	10.34	9.44	8.09	7.62	7.27	6.92	6.56	6.22	6.03										
9	$\frac{T_{min}}{D_1}$	19.12	16.77	14.93	12.15	11.44	10.69	10.08	9.63	9.07	8.64										
10	$D_1 + \frac{V_1^2}{2g}$	4.262	4.244	4.234	4.238	4.212	4.226	4.224	4.192	4.188	4.204										
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18										
		Diving Flow Conditions																			
12	T (diving depth)	3.40	3.03	3.01	2.46	2.38	2.44	2.44	2.32	2.46	2.37	2.68	2.39	2.37	2.42	3.07	1.96	1.86	2.23	2.69	2.43
13	T_{max}	2.90	2.53	2.51	1.96	1.88	1.94	1.94	1.82	1.96	1.87	2.18	1.89	1.87	1.92	2.57	1.46	1.36	1.73	2.19	1.93
14	$\frac{V_1^2}{2g} = X + H - T_{max}$	1.519	1.946	2.021	2.682	2.802	2.782	2.824	2.985	2.892	2.014	2.354	2.688	2.715	2.713	1.970	2.970	3.125	2.797	2.444	2.793
15	V_1	9.89	11.20	11.40	13.14	13.43	13.40	13.48	13.87	13.65	13.94	12.31	13.16	13.22	13.21	11.26	13.84	14.18	13.42	12.55	13.40
16	D_1	0.106	0.114	0.133	0.156	0.170	0.187	0.203	0.216	0.242	0.252	0.126	0.131	0.135	0.153	0.138	0.081	0.093	0.112	0.160	0.187
17	$F = \frac{V_1}{\sqrt{gD_1}}$	5.34	5.84	5.49	5.85	5.72	5.46	5.26	5.25	4.89	4.89	6.11	6.41	6.38	5.95	4.15	8.59	8.19	7.08	5.53	5.46
18	$\frac{T_{max}}{D_1}$	2.733	22.13	18.82	12.56	11.07	10.39	9.54	8.54	8.10	7.40	17.28	14.38	13.89	12.55	18.55	18.00	14.60	15.47	13.67	10.34
19	$D_1 + \frac{V_1^2}{2g}$	1.625	2.060	2.154	2.838	2.972	2.969	2.077	3.201	3.134	3.266	2.480	2.819	2.850	2.866	2.108	3.054	3.218	2.909	2.604	2.980
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.46	0.36	0.35	0.26	0.25	0.25	0.25	0.23	0.24	0.23	0.30	0.27	0.26	0.26	0.35	0.25	0.23	0.26	0.29	0.25

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweepout depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Maximum capacity of bucket estimated to be 2.0 to 2.5 second-feet per foot of width.

FIGURF 16



A. q = 2.5 c.f.s.

B. q = 3.0 c.f.s.

C. q = 3.5 c.f.s.

D. q = 4.0 c.f.s.

(Bed level 0.6-inch below apron lip at start of test.)

12-INCH BUCKET — TAILWATER DEPTH = 2.30 FEET

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Table V

DATA AND CALCULATED VALUES FOR 12-INCH RADIUS BUCKET

	Run No.	Bed was approximately 0.05R below apron lip at beginning of each run												Bed slopes up from apron lip			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
									Sweepout Conditions								
1	H	0.543	0.592	0.637	0.679	0.729	0.765	0.811	0.850	0.887	0.961	1.02	1.221	0.565	0.651	0.723	0.839
2	T (sweepout depth)	1.27	1.33	1.40	1.45	1.52	1.56	1.68	1.72	1.78	1.89	1.96	2.23				
3	q	1.58	1.82	2.03	2.25	2.53	2.75	3.05	3.28	3.54	4.06	4.48	6.08	1.67	2.00	2.50	3.21
4	T_{min}	1.47	1.53	1.60	1.65	1.72	1.76	1.88	1.92	1.98	2.09	2.16	2.43				
5	$\frac{V_1^2}{2g} = X + H - T_{min}$	4.073	4.062	4.037	4.029	4.009	4.005	3.931	3.930	3.907	3.871	3.860	3.791				
6	V_1	16.20	16.17	16.12	16.11	16.07	16.06	15.92	15.91	15.86	15.79	15.77	15.63				
7	D_1	0.099	0.112	0.126	0.140	0.157	0.171	0.192	0.206	0.223	0.257	0.284	0.389				
8	$F = \frac{V_1}{\sqrt{gD_1}}$	9.10	8.51	8.01	7.60	7.14	6.84	6.41	6.18	5.93	5.49	5.22	4.42				
9	$\frac{T_{min}}{D_1}$	14.91	13.60	12.71	11.81	10.93	10.28	9.81	9.31	8.87	8.13	7.60	6.25				
10	$D_1 + \frac{V_1^2}{2g}$	4.172	4.175	4.163	4.169	4.166	4.176	4.123	4.136	4.133	4.128	4.144	4.180				
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24				
									Diving Flow Conditions								
12	T (diving depth)	3.95	4.00	3.90	3.95	3.95	3.95	--	2.91	2.87	3.22	3.17	3.00	3.25	3.00	2.45	2.35
13	T_{max}	3.45	3.50	3.40	3.45	3.45	3.45	--	2.41	2.37	2.72	2.67	2.50	2.75	2.50	1.95	1.85
14	$\frac{V_1^2}{2g} = X + H - T_{max}$	1.093	1.092	1.237	1.229	1.279	1.315	--	2.440	2.517	2.241	2.35	2.721	1.815	2.131	2.773	2.889
15	V_1	8.39	8.39	8.92	8.90	9.07	9.20	--	12.54	12.72	12.01	12.30	12.23	10.81	11.71	13.36	13.64
16	D_1	0.188	0.217	0.228	0.253	0.279	0.299	--	0.262	0.278	0.338	0.364	0.460	0.154	0.171	0.187	0.235
17	$F = \frac{V_1}{\sqrt{gD_1}}$	3.42	3.17	3.29	3.11	3.02	2.96	--	4.31	4.25	3.64	3.41	3.44	4.86	4.98	5.54	4.96
18	$\frac{T_{max}}{D_1}$	18.35	16.12	14.91	14.63	12.36	11.53	--	9.19	8.52	8.04	7.33	5.54	17.85	14.61	10.42	7.87
19	$D_1 + \frac{V_1^2}{2g}$	1.281	1.309	1.465	1.482	1.558	1.614	--	2.702	2.795	2.579	2.714	3.181	1.969	2.302	2.960	3.124
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.78	0.72	0.68	0.67	0.64	0.62		0.37	0.36	0.39	0.37	0.31	0.51	0.43	0.34	0.32

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweepout depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Maximum capacity of bucket estimated to be 3.25 to 3.50 second-feet per foot of width.

for the 9-inch bucket. The safe maximum limit appeared to be about the same as the upper limit for the 9-inch bucket with the bed molded level below lip elevation. These data are also given in Table V and plotted in Figure 11. The maximum capacity of the 12-inch bucket was considered to be the same with the upward sloping bed as with the level bed.

Eighteen-inch Radius Bucket

The 5-foot-high model spillway with the 18-inch bucket represented a relatively low structure such as a diversion dam spillway.

The performance of the 18-inch bucket is shown in Figure 17 for discharges ranging from 6 to 11 second-feet with normal tail water depths. The capacity of the bucket was estimated to be 5 to 5.5 second-feet per foot of width.

With the movable bed molded level, approximately 0.05R or 0.9 of an inch below the apron lip, tests for sweepout were made and the data obtained are recorded in Table VI and plotted in Figure 22. Depths for sweepout and diving were even more difficult to determine precisely than for the smaller buckets. In fact, the sustained diving condition could not be reached by raising the tail water as high as possible in the model for any discharge. However, the tendency to dive was present and momentary diving occurred, but in no case was it sustained.

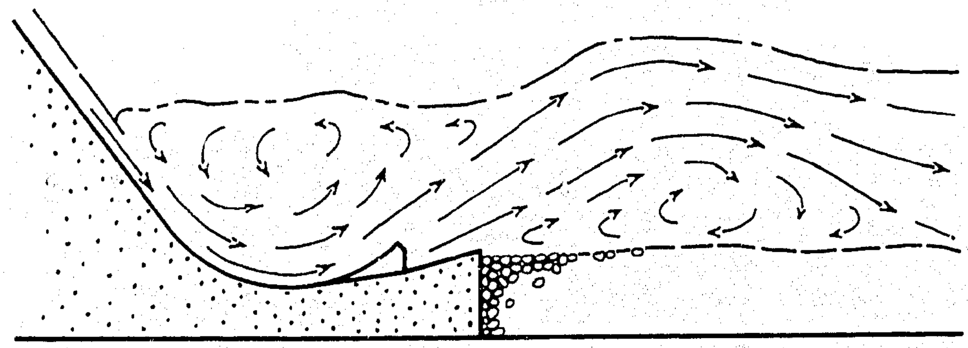
The minimum tail water depth at which the bucket operated satisfactorily was found to be 0.1 foot above the sweepout depth, however, 0.2 foot was used, as for the other buckets, to provide a factor of safety.

The maximum tail water limit or the maximum bucket capacity were not determined using the sloping bed because of difficulties in maintaining the bed shape while starting a test run. Performance with the sloping bed was, therefore, assumed to be consistent with the test results on the 9- and 12-inch radius buckets.

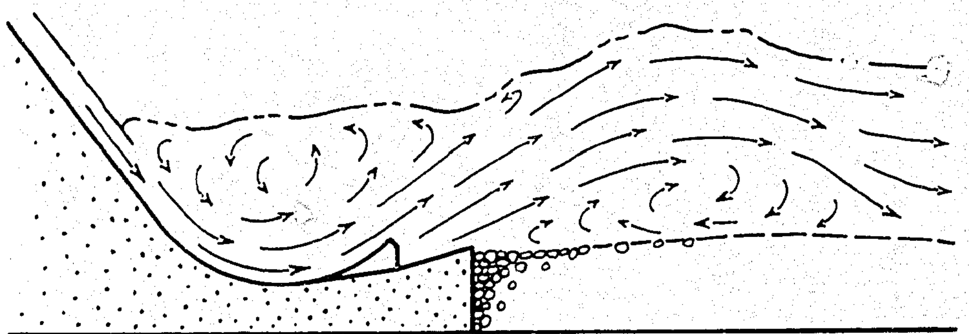
Larger and Smaller Buckets

Larger buckets were not tested with this 5-foot spillway because of the increasing difficulties in measuring bucket capacity and tail water depth limits for near capacity flows and because a larger bucket operating at near maximum tail water depth limit would either submerge the crest or, closely, approach that condition. It was not intended at this time to investigate a bucket with a submerged crest.

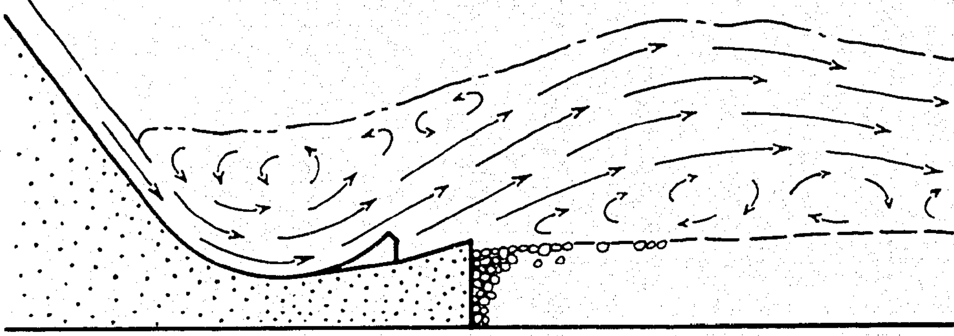
Smaller buckets were not tested because very few, if any, prototype structures would use a bucket radius smaller than one-tenth



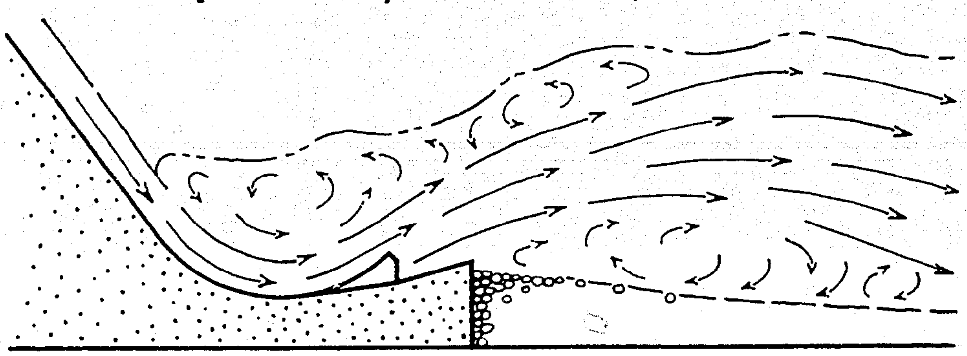
A. q = 3 c.f.s., Tailwater depth = 2.30 feet.



B. q = 3.5 c.f.s., Tailwater depth = 2.30 feet.



C. q = 4 c.f.s., Tailwater depth = 2.30 feet.



D. q = 5.5 c.f.s., Tailwater depth = 2.45 feet

(Bed level 0.9-inch below apron lip at start of test.)

18-INCH BUCKET PERFORMANCE

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Table VI

DATA AND CALCULATED VALUES FOR 18-INCH RADIUS BUCKET

	Run No.	Bed was approximately 0.05R below apron lip at beginning of each run							
		1	2	3	4	5	6	7	8
					Sweepout Conditions				
1	H	0.631	0.734	0.804	0.898	0.926	1.001	1.083	1.150
2	T (sweepout depth)	1.45		1.78					
3	q	2.00	2.56	2.99	3.61	3.80	4.35	4.98	5.48
4	T_{min}	1.65	1.85	1.98	2.07	2.15	2.23	2.32	2.45
5	$\frac{V_1^2}{2g} = X + H - T_{min}$	3.981	3.884	3.824	3.828	3.776	3.771	3.763	3.700
6	V_1	16.02	15.86	15.70	15.70	15.27	15.68	15.67	15.44
7	D_1	0.125	0.161	0.190	0.230	0.249	0.277	0.318	0.355
8	$F = \frac{V_1}{\sqrt{gD_1}}$	7.98	6.94	6.33	6.76	5.39	5.24	4.88	4.56
9	$\frac{T_{min}}{D_1}$	13.22	11.46	10.39	9.00	8.64	8.03	7.30	6.70
10	$D_1 + \frac{V_1^2}{2g}$	4.106	4.045	4.014	4.058	4.025	4.043	4.081	4.055
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
					Diving Flow Conditions				
12	T (diving depth)								
13	T_{max}								
14	$\frac{V_1^2}{2g} = X + H - T_{max}$								
15	V_1								
16	D_1								
17	$F = \frac{V_1}{\sqrt{gD_1}}$				NO DATA TAKEN				
18	$\frac{T_{max}}{D_1}$								
19	$D_1 + \frac{V_1^2}{2g}$								
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$								

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweepout depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Maximum capacity of bucket estimated to be 5.0 to 5.5 second-feet per foot of width.

the height of the spillway. Small radii bends are usually avoided on high structures where velocities are also high. Therefore, the available data were analyzed, and with some extrapolation, found to be sufficient.

Data Analysis

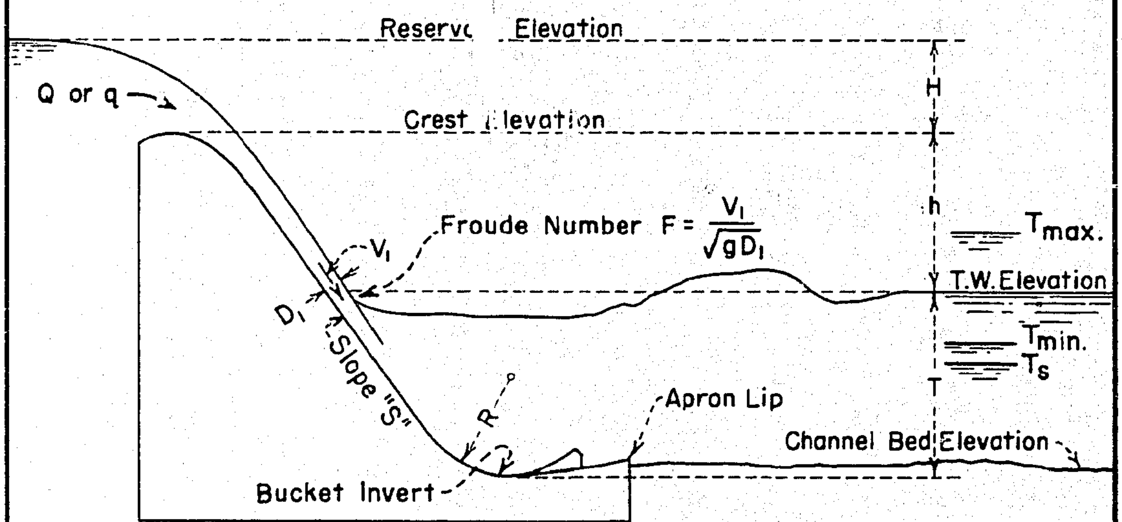
Safety factor. At the conclusion of the testing the data for the four buckets were surveyed and the margin of safety between sweepout depth and minimum tail water depth, and between maximum tail water depth and the depth required for diving were definitely established. An ample margin of safety for the lower limit was 0.2 foot and for the upper limit 0.5 foot. These values were sufficient for both the level and sloping movable beds previously described. The selected margins of safety are included in items T_{min} and T_{max} of Tables III, IV, V, and VI.

Evaluation of variables. To generalize the data in such a way that it can readily be used to determine the minimum allowable bucket radius "R," the safe minimum tail water depth "T_{min}" and the safe maximum tail water depth "T_{max}" for any prototype overflow spillway whose crest is not submerged by the tail water, it is necessary to consider the variables, shown in Figure 18, that affect the unknown requirements. The maximum capacity of a given radius bucket is increased slightly when the tail water depth is at an intermediate value between the minimum or maximum tail water depths, but since buckets are usually expected to operate over a range of tail water depths the bucket capacity is not a function of tail water depth.

The elevation of the movable bed with respect to the apron lip and the slope of the spillway face do not, within ordinary limits, affect the sweepout depth or the size of bucket. Frictional resistance on the spillway face affects the minimum depth limit, the maximum depth limit, and the minimum allowable bucket radius since head losses caused by skin friction reduce the effective height of fall. However, frictional resistance is, primarily, a function of head or discharge and the height of spillway above tail water elevation; therefore, friction effects need not be considered as a separate variable. The effect of friction losses is discussed further in a following portion of this report.

Data obtained during the tests includes the sweepout and diving depths for a given height of model spillway above tail water elevation "h." The given slope of spillway is "S." Figure 11 shows that the sweepout depth is a function of the radius of bucket "R" and the head on the crest "H." "H" may also be expressed in terms of discharge "q" per foot of spillway width; however, "q" and "H" are related by the discharge coefficient "c" in the discharge equation

FIGURE 18



DEFINITION OF SYMBOLS

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$$q = cH^{3/2}$$

Therefore,

$$T_{min} = f(h, S, R, H \text{ and } q)$$

Figure 11 also shows the tail water depth at which diving flow occurred to depend upon the elevation of the channel bed with respect to the apron lip, the bucket radius, and the head on the crest. Therefore

$$T_{max} = f(h, S, R, H, q \text{ and elevation of channel bed in relation to elevation of bucket apron lip})$$

The minimum allowable bucket radius for a given height of model spillway above tail water elevation, with given slope of spillway, is a function only of the head on the crest, Figure 11. Therefore, the minimum allowable bucket radius R_{min} may be expressed:

$$R_{min} = f(h, S, H \text{ and } q)$$

The velocity entering the bucket "V_1" and depth "D_1" are functions of head, discharge, height of spillway above tail water elevation, and spillway slope.

$$V_1 \text{ and } D_1 = f(h, S, H \text{ and } q)$$

The Froude number, a dimensionless parameter, is a function of velocity and depth of flow and may be expressed

$$F = \frac{V_1}{\sqrt{gD_1}}$$

Substituting F for h, S, H and q

$$T_{min} = f(R, F)$$

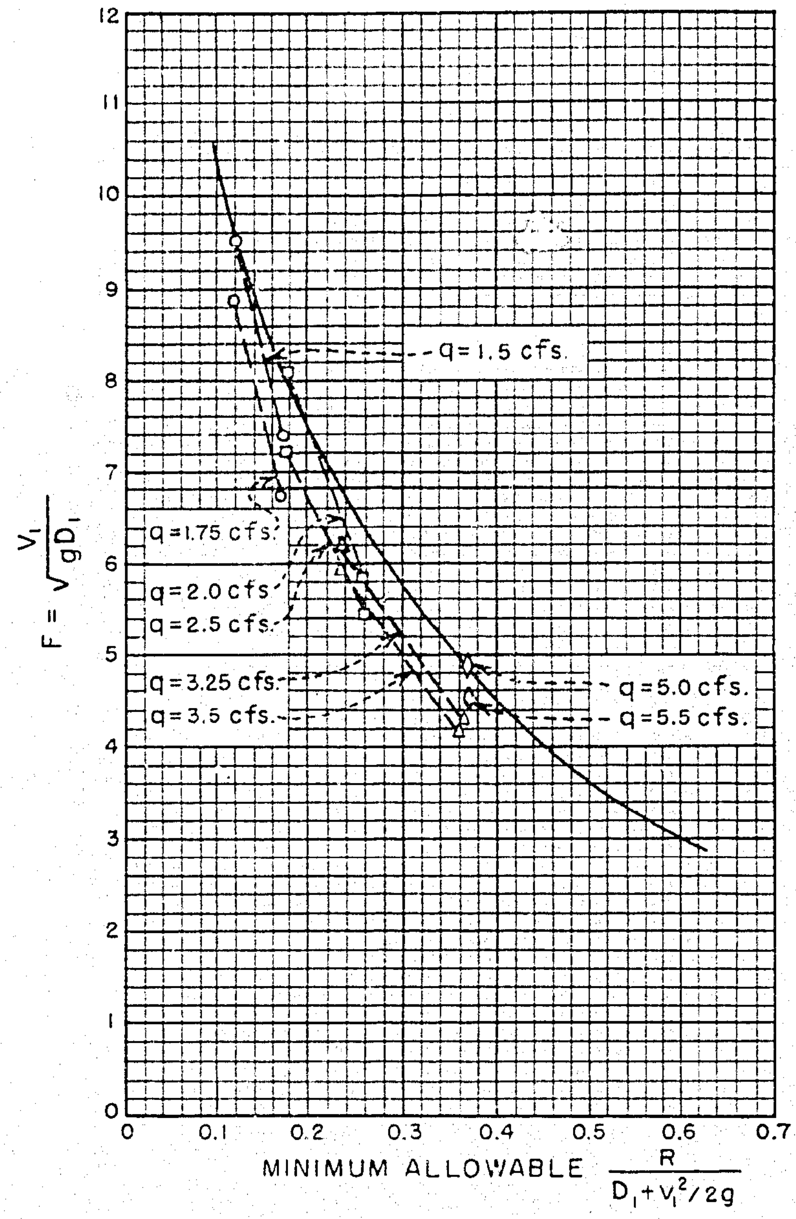
$$T_{max} = f(R, F, \text{ and elevation of channel bed with respect to apron lip})$$

$$R_{min} = f(F)$$

Numerical values for the Froude number were computed from the available test data in the tables for points at the intersection of the spillway face and the tail water surface. At these points all necessary information for computing velocity and depth of flow can be determined from the available test data which includes reservoir elevation, discharge, and tail water elevation. Since the Froude number expresses a ratio of velocity to depth and is dimensionless, a numerical value represents a prototype as well as a model flow condition.

To express T_{min}, T_{max}, and R as dimensionless numbers so that they may also represent prototype flow conditions, T_{min} and T_{max} were divided by D_1; R was divided by $D_1 + V_1^2/2g$, the depth of flow plus the velocity head at tail water elevation on the spillway face. These dimensionless ratios and the Froude number, computed from test data, are shown in Tables III, IV, V, and VI. In computing the tabular values, frictional resistance in the 5-foot model was considered to be negligible. In Figure 19 the dimensionless ratio for the bucket radius is plotted against the Froude number, using only the test points bracketing the estimated maximum bucket capacity. Values were computed for both the sweepout and diving tail water elevations since the Froude number and $\frac{R}{D_1 + \frac{V_1^2}{2g}}$ both vary with tail water elevation. For example, the maximum capacity of the 6-inch bucket is q = 1.5 to 1.75 in columns 7 and 8 of Table III; data from lines 8 and 11 and lines 17 and 20 were plotted in Figure 19. The two points thus obtained for each discharge were connected by a dashed line to indicate the trend for constant discharge. Eight dashed lines were thereby obtained for the four buckets. A single envelope curve was then drawn, shown as the solid line to the right of the preliminary lines, to represent the minimum radius bucket. The solid line therefore includes a factor of safety. If a larger factor of safety is desired, the solid curve may be moved to the right as far as is considered necessary.

Since both the upper and lower depth limits are functions of the bucket radius and the Froude number, $\frac{T_{min}}{D_1}$ and $\frac{T_{max}}{D_1}$ for each test point in Tables III through VI were plotted versus the Froude number in Figure 20, and each curve was labeled with the computed values of $\frac{R}{D_1 + \frac{V_1^2}{2g}}$. Since the upper tail water depth limit varied with shape and elevation of the movable bed, two sets of upper tail water depth dimensionless ratios were plotted, one for each of the two bed elevations tested. The curves drawn through these points in Figure 20 may be used to determine minimum and maximum tail water depth limits for any given Froude number and bucket radius.



EXPLANATION

- ○ For bucket radius (R) = 6 inches
- □ For bucket radius (R) = 9 inches
- △ For bucket radius (R) = 12 inches
- ◊ For bucket radius (R) = 18 inches

Bed level approximately 0.05R below lip of apron.

MINIMUM ALLOWABLE BUCKET RADIUS

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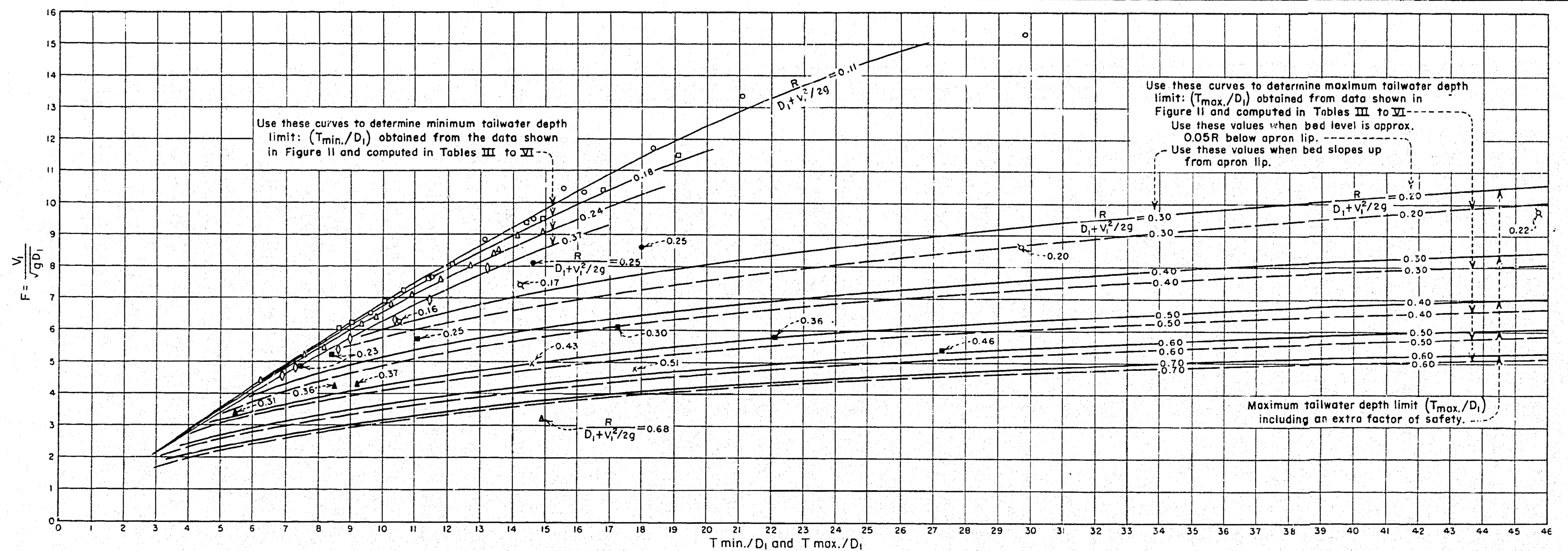
FIGURE 20



DATA SYMBOL	BUCKET RADIUS (R) INCHES	$\frac{R}{D_1+V_1^2/2g}$	BED ARRANGEMENT	DESCRIPTION OF DATA POINT
○	6	0.11	For any position of the bed	Min. tailwater depth limit
□	9	0.16	For any position of the bed	Min. tailwater depth limit
△	12	0.24	For any position of the bed	Min. tailwater depth limit
◊	18	0.37	For any position of the bed	Min. tailwater depth limit
◊ (flagged)	6	0.16 to 0.22	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
■	9	0.23 to 0.46	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
▲	12	0.31 to 0.68	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
●	9	0.25	For bed sloping up from apron lip	Max. tailwater depth limit
x	12	0.43 to 0.51	For bed sloping up from apron lip	Max. tailwater depth limit

DIMENSIONLESS PLOT OF MAXIMUM AND MINIMUM TAILWATER DEPTH LIMITS

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Note that the upper four curves in Figure 20 are for the minimum tail water condition and apply to any bed arrangement. The ten lower curves extending far to the right apply to the maximum tail water limitation and have two sets of labels, one for the sloping bed and one for the level bed. Two curves are shown for each value of $\frac{R}{D_1 + \frac{V_1^2}{2g}}$; the upper or solid line curve has an extra factor of safety included while the lower or dashed line curve is according to the data in Tables II through IV.

Although the curves of Figure 20 may be used as shown, a simpler and easier to use version of the same data is given in Figures 21 and 22. Figure 21 contains a family of curves to determine $\frac{T_{min}}{D_1}$ values in terms of the Froude number and $\frac{R}{D_1 + \frac{V_1^2}{2g}}$. Figure 22 contains similar curves to determine $\frac{T_{max}}{D_1}$ and includes the extra factor of safety discussed for Figure 22. The two abscissa scales in Figure 22 differentiate between the standard sloping bed and the standard level bed used in the tests. Figures 21 and 22 were obtained by cross-plotting the curves of Figure 20.

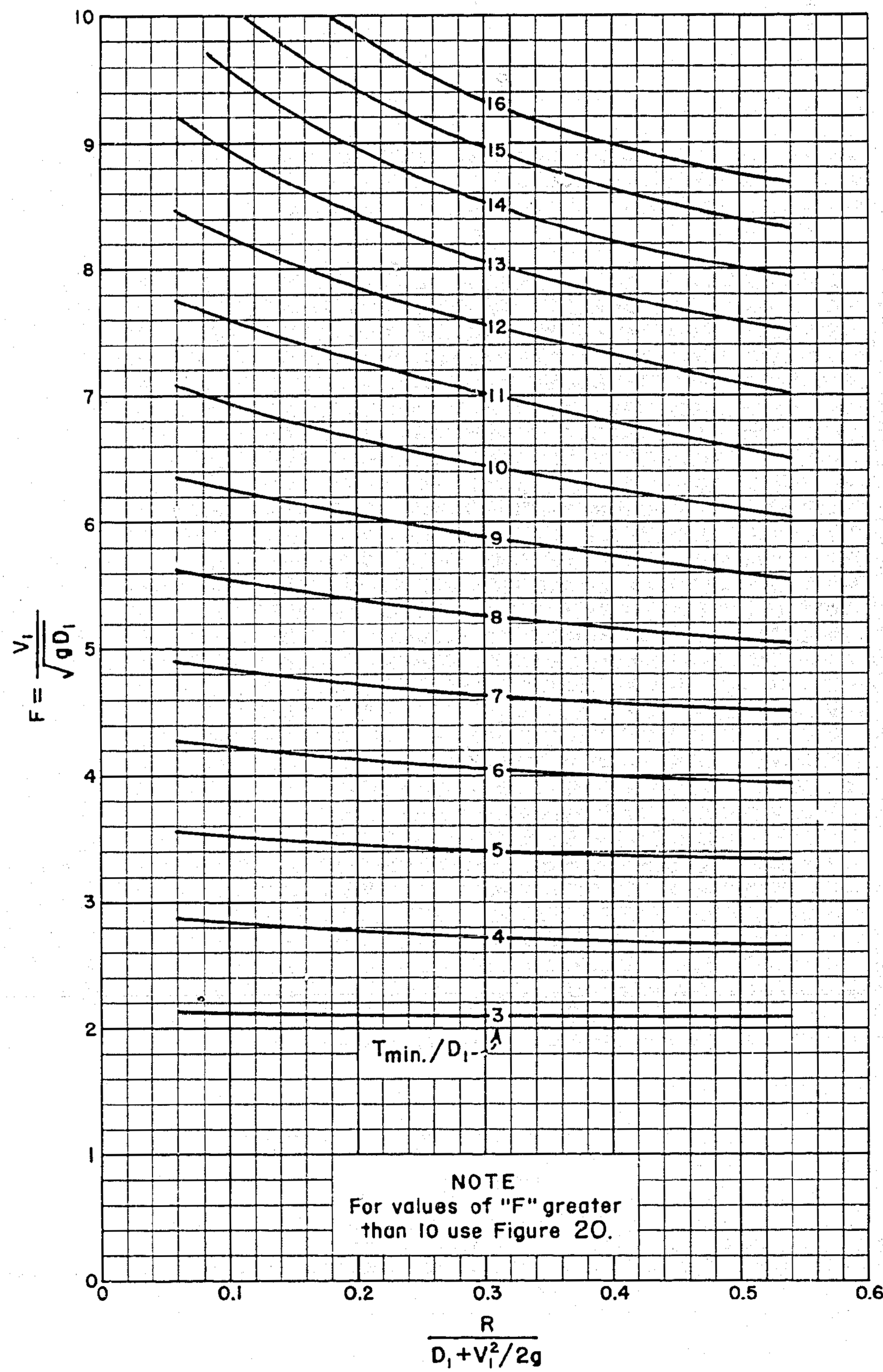
The tail water sweepout depth "T" in Tables III through VI was also expressed as a dimensionless ratio $\frac{T_s}{D_1}$ and plotted versus the Froude number in Figure 23, and a curve for each bucket size was drawn. These curves were then cross-plotted in Figure 24 to provide a simple means for determining the sweepout depth for any installation. The difference between sweepout depth and the depth actually encountered indicates the margin of safety.

Practical Applications

To illustrate the use of the methods and charts given in this report, a step by step procedure for designing a slotted bucket is presented. The data for Grand Coulee Dam spillway will be used as an example. The calculations are summarized in Table VII.

For maximum reservoir elevation 1290 at Grand Coulee Dam the spillway discharge is 935,000 second-feet. Since the spillway crest is at elevation 1260 the head is 30 feet. The length of the crest is 1,485 feet making the discharge per foot of bucket width 630 second-feet. The tail water in the river is expected to be at elevation 1009 for the

FIGURE 21



MINIMUM TAILWATER LIMIT

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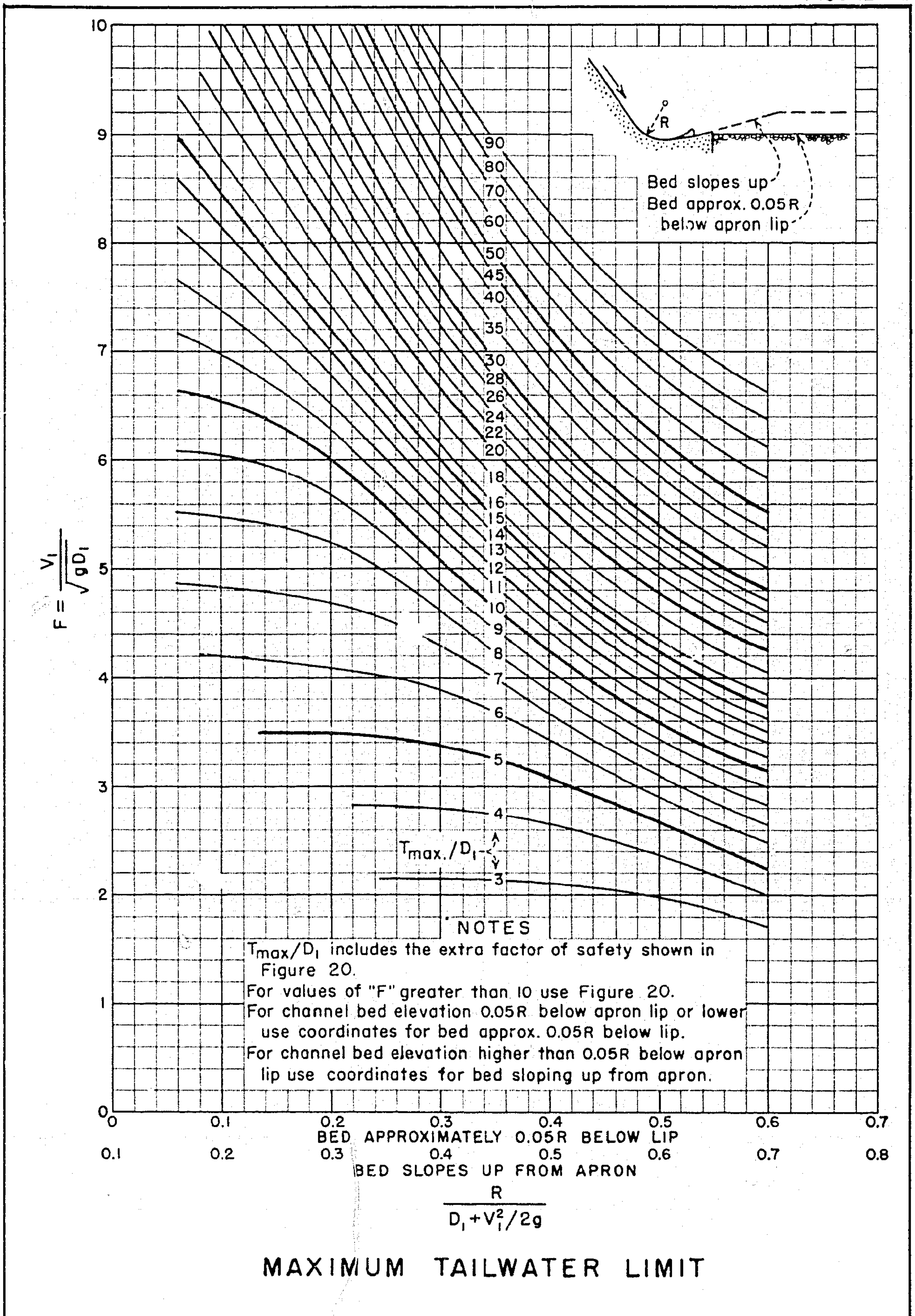
FIGURE 22



MAXIMUM TAILWATER LIMIT

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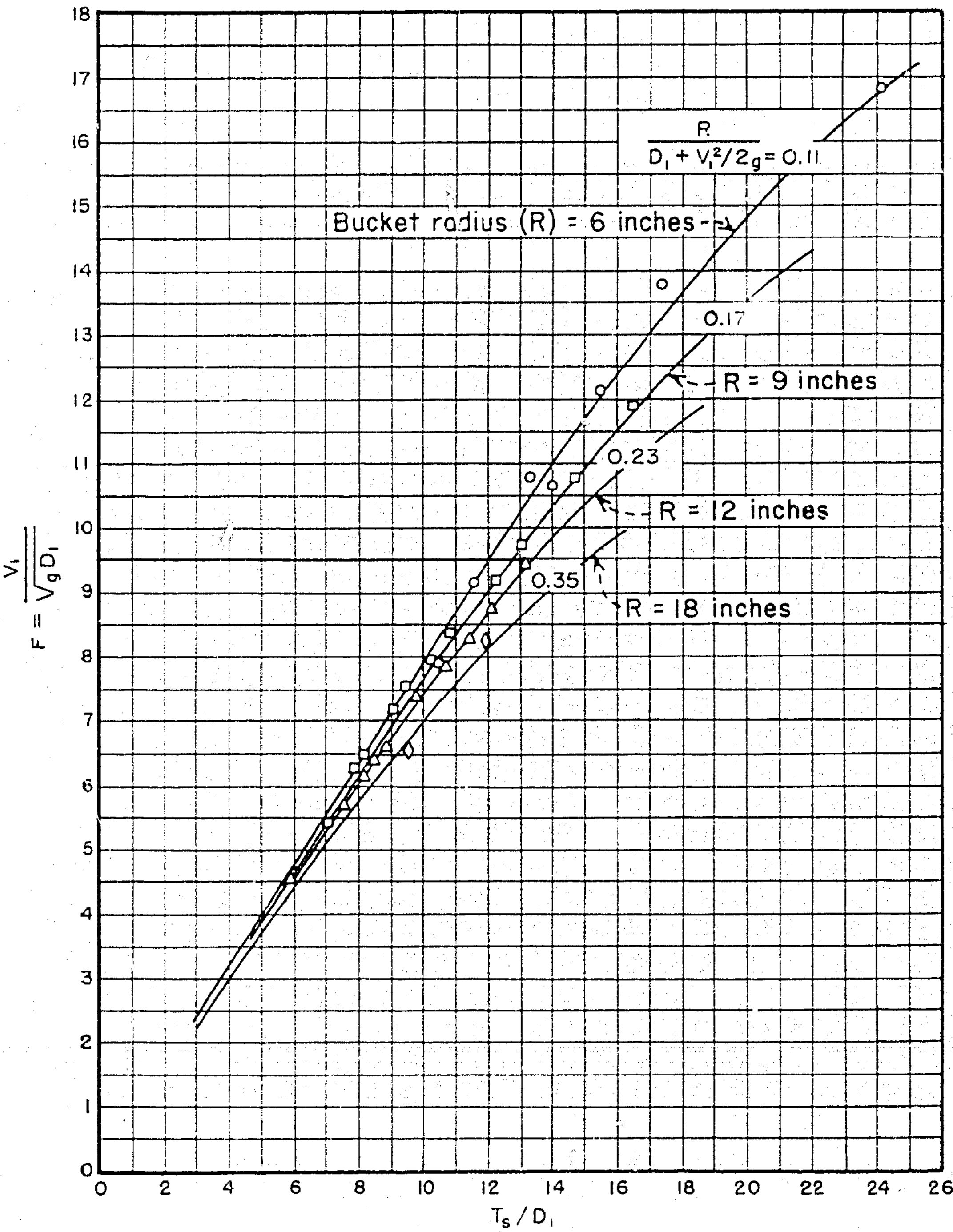
FIGURE 23



Note: Bed arrangement not critical for sweepout condition

TAILWATER DEPTH AT SWEEPOUT

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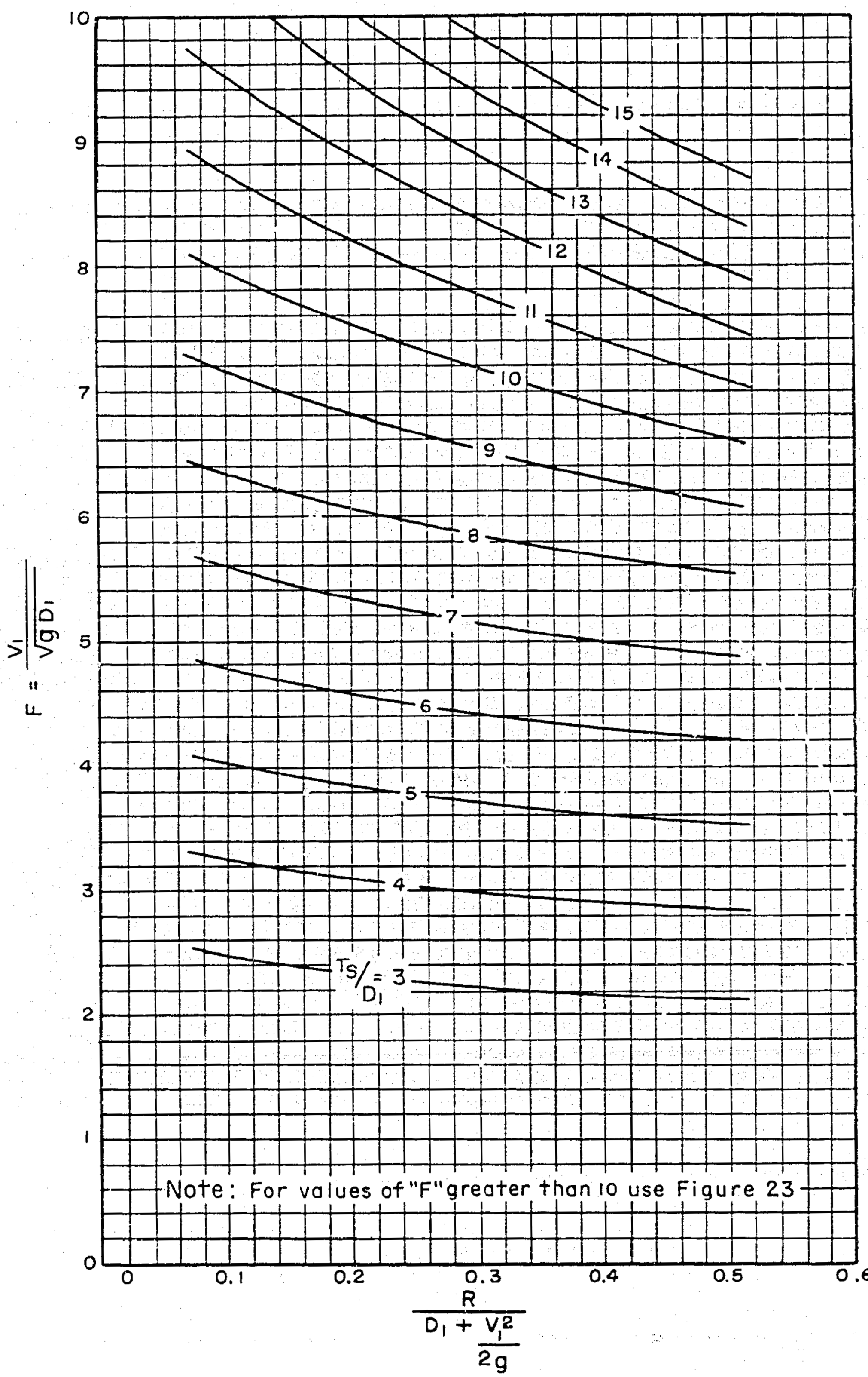

TAILWATER SWEEPOUT DEPTH

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Table VII

EXAMPLES OF BUCKET DESIGN PROCEDURES

		Angostura Dam	Angostura Dam	Angostura Dam	Angostura Dam	Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam
1	Q	247,000	180,000	100,000	40,000	935,000	133,000	90,000
2	Reservoir elevation	3198.1	3191.0	3181.5	3170.4	1290	2785	2043.4
3	Crest elevation	3157.2	3157.2	3157.2	3157.2	1260	2743	2032
4	H	40.9	33.8	24.3	13.2	30	42	17.4
5	L	274	274	274	274	1485	266	644
6	q	901	657	365	146	630	500	140
7	Tail water elevation	3114	3106	3095	3084	1009	2700.5	2018.3
8	$\frac{V_1^2}{2g}$ (theoretical) = (2) - (7)	84.1	85.0	86.5	86.4	281	84.4	25.1
9	V_1 (theoretical)	73.6	74	75	75	130.5	73.7	40.2
10	$\frac{V_1 \text{ (actual)}}{V_1 \text{ (theoretical)}}$	0.98	0.98	0.97	0.93	0.91	0.90	0.98
11	V_1 (actual)	72.2	72.5	72.8	69.8	118.8	66.0	39.4
12	$\frac{V_1^2}{2g}$ (actual)	80.9	81.6	82.3	75.6	219.2	67.6	24.1
13	D_1	12.48	9.06	5.01	2.09	5.30	7.58	3.55
14	$\sqrt{D_1}$	3.53	3.00	2.24	1.45	2.30	2.75	1.88
15	$F = \frac{V_1}{\sqrt{gD_1}}$	3.61	4.26	5.73	8.49	9.11	4.23	3.70
16	$D_1 + \frac{V_1^2}{2g}$	93.38	90.66	87.31	77.69	224.50	75.18	27.65
17	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$ (minimum)	0.50	0.43	0.30	0.15	0.13	0.43	0.48
18	R (minimum)	47	39	26	12	29	33	13
19	R (actually used)	40	40	40	40			
20	R (recommended)					30	35	12.5
21	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$ (actual)	0.43	0.44	0.46	0.51	0.13	0.47	0.45
22	$\frac{T_{min}}{D_1}$	5.4	6.6	9.3	16.4	13.8	6.6	5.5
23	T_{min}	67	60	46	34	73	50	20
24	$\frac{T_{max}}{D_1}$	5.6	7.9	17.6	60.0	18.8	13.0	8.8
25	T_{max}	70	72	88	125	100.7	99	31
26	$\frac{T_s}{D_1}$	5.0	6.0	8.0	14.4	11.8	5.7	5.0
27	T_s	62	54	40	30	63	44	18

Q = total discharge (cfs)
L = bucket width (ft)
q = discharge per foot of bucket width (cfs)
H = height of reservoir above crest (ft)
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation
R = bucket radius (ft)
T_{min} = minimum tail water depth limit (ft)
T_{max} = maximum tail water depth limit (ft)
T_s = tail water sweepout depth (ft)

Line 10 from Figure 25
Line 17 from Figure 19
Line 22 from Figure 21
Line 24 from Figure 22
Line 26 from Figure 24

maximum flow. The velocity head of the flow entering the basin at tail water elevation on the spillway face is the difference between tail water elevation and reservoir elevation or 281 feet. Then, theoretically, the velocity, "V_1," entering the tail water is 130.5 feet per second; $V_1 = \sqrt{2g(h + H)}$.

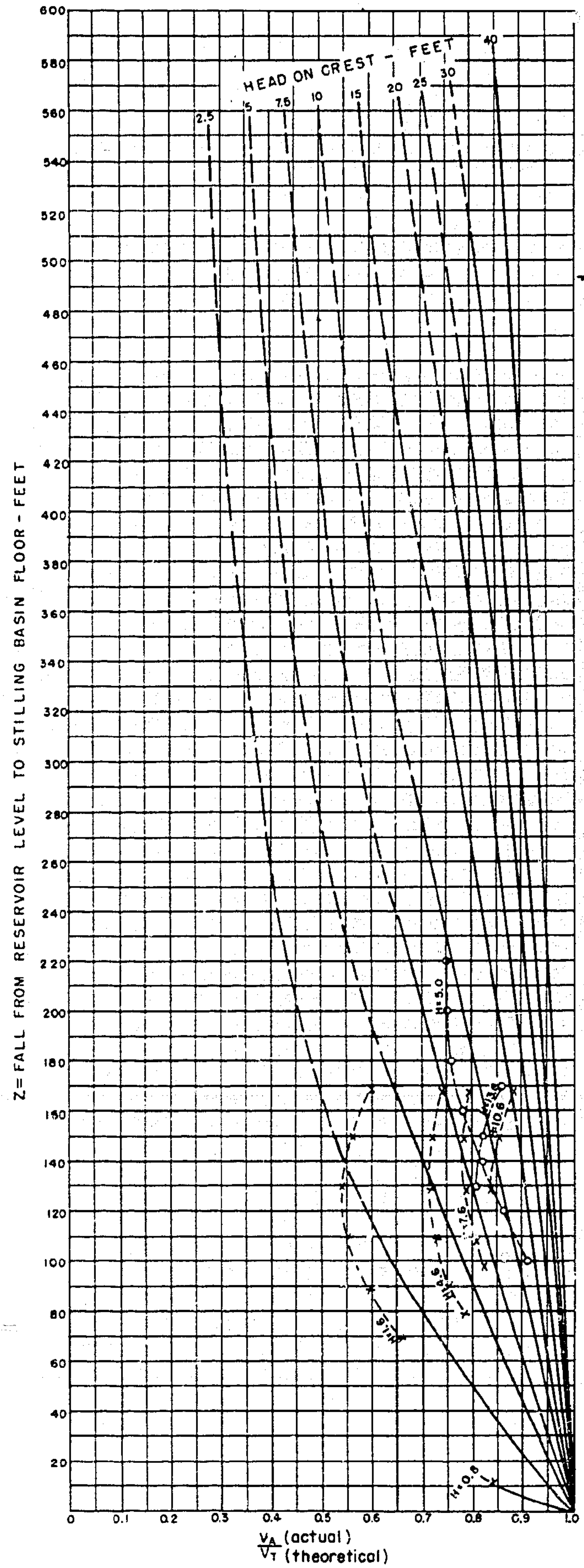
The actual velocity and velocity head are less than theoretical at this point, however, due to frictional resistance on the spillway face. Using Figure 25, the actual velocity is found to be 91 percent of theoretical. Figure 25 was prepared to reduce the computation work on the preliminary design of overfall spillways and is believed to be reasonably accurate. However, only a limited amount of prototype data was available to develop the chart so that the data obtained from the chart should be used with caution. Entering Figure 25 with the height of fall of 281 feet as the ordinate, and intersecting the curve for 30 feet of head on the crest, the abscissa is found to be 0.91. Therefore, the actual velocity in this example is 91 percent of 130.5 or 118.8 feet per second and the corresponding velocity head is 219.2 feet. The corresponding depth of flow D_1 on the spillway face is $\frac{q}{V_1}$ or 5.3 feet. Having determined D_1 and V_1, the Froude number, $F = \frac{V_1}{\sqrt{gD_1}}$, is computed to be 9.11.

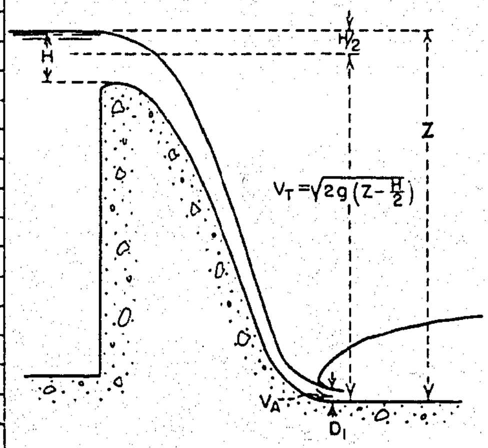
Entering Figure 19 with Froude number 9.11, the dimensionless ratio of the minimum usable bucket radius is found to be 0.13 from the solid line envelope curve. The minimum allowable bucket radius is then computed to be 29 feet. In round numbers a 30-foot bucket radius would probably be used. For the 30-foot radius the bucket radius dimensionless ratio would remain 0.13. Entering Figure 21 with the bucket radius dimensionless ratio and the Froude number, $\frac{T_{min}}{D_1}$ is found to be 13.8. The minimum tail water depth limit is then 73 feet, measured from the bucket invert to the tail water surface elevation. Entering Figure 22 with the dimensionless ratio of the bucket radius and the Froude number, $\frac{T_{max}}{D_1}$ for bed elevation below the apron lip is found to be 18.8. The maximum tail water depth limit is then 100 feet.

The riverbed at Grand Coulee Dam is at elevation 900, approximately. If the bucket invert is placed at riverbed elevation the tail water depth would be 109 feet which exceeds the upper limit of 100 feet. Therefore, the bucket should be set above the riverbed so that the tail water depth from the bucket invert will be between 73 and 100 feet.

The bucket would then perform as shown in Figures 12A or B. Performance similar to Figure 12A would be preferred but the performance

FIGURE 25





PROTOTYPE TESTS
X Shasta Dam
O Grand Coulee Dam

HYDRAULIC JUMP STUDIES

CURVES FOR DETERMINATION OF VELOCITY ENTERING STILLING BASIN FOR STEEP SLOPES 0.8:1 TO 0.6:1

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shown in Figure 12B would be acceptable. Performance similar to that in Figure 12A will occur if the bucket invert is placed so that the tail water depth is close to the lower limit. A tail water depth of between 75 and 80 feet would probably be most satisfactory.

To determine the sweepout depth enter Figure 24 with the Froude number and the bucket radius dimensionless ratio; the sweepout depth dimensionless ratio is 11.8. The sweepout depth then is approximately 63 feet. Thus, the minimum tail water depth limit of 73 feet provides approximately 10 feet of margin against flow sweeping out of the bucket at the maximum discharge. Therefore, the bucket invert should be set to provide about 75 feet of tail water depth.

Another solution for the Grand Coulee example presented here would be to use a larger radius bucket if for some reason the bucket could not be elevated. A larger usable range of tail water will also be obtained. For example, instead of using the minimum 30-foot radius bucket, try a 50-foot radius bucket. The bucket radius dimensionless ratio then would have a value of 0.23, and from Figure 21 the minimum tail water depth limit dimensionless ratio is 15, and from Figure 22 the maximum tail water depth limit dimensionless ratio is 33. The lower tail water depth limit is therefore 80 feet and the upper limit 175 feet.

If the invert of the bucket is placed at riverbed elevation 900, the tail water depth would be 109 feet which is well within the two limits. However, if the bucket invert was placed below riverbed and the bed was sloped upward from the apron, the dimensionless ratio of the maximum tail water depth limit would be approximately 19 as found in Figure 22. The upper depth limit therefore would be only 100 feet. The tail water depth would be greater than 109, therefore, riverbed scouring would probably occur as a result of diving flow.

Before adopting either of the buckets discussed, intermediate discharges should also be investigated, taking into account the fact that the bucket might be required to operate at maximum discharge with tail water corresponding to the discharge just before it was increased to maximum, and perhaps without the additional tail water depth created by powerplant discharge. After the bucket radius has been determined, the bucket design may be completed from the data in Figure 1.

The investigation of partial discharges is shown in Table VII for the Angostura Dam spillway where the bucket actually determined from model tests is shown, using the methods and curves in this report, to be undersized for the maximum discharge, correct for three-fourths maximum, and oversized for smaller discharges.

The fact that the methods of this report show the need for a larger bucket than was built for Angostura indicates that a factor of safety is included in the charts in this report. This is a desirable feature when hydraulic model studies are not contemplated. On the other hand, hydraulic model studies make it possible to explore regions of uncertainty in any particular case and help to provide the minimum bucket size consistent with acceptable performance.

Other examples in Table VII include an analysis using the data for Trenton Dam spillway. This spillway utilizes a long flat chute upstream from the energy dissipator. Friction losses are considerably higher than would occur on the steep spillways for which Figure 24 was drawn and other means must be used to obtain V_1 and D_1 for the bucket design. In the example in Table VII, actual velocity measurements taken from a model were used. If frictional resistance is neglected in the velocity computations, the minimum tail water limit would be higher, providing a greater factor of safety against sweepout, but the maximum tail water limit would also be higher which reduces the factor of safety against flow diving.

Tail water requirements for bucket versus hydraulic jump. In general, a bucket-type dissipator requires a greater depth of tail water than a stilling basin utilizing the hydraulic jump. This is illustrated in Table VIII where pertinent data from Table VII is summarized to compare the minimum tail water depth necessary for a minimum radius bucket with the computed conjugate tail water depth for a hydraulic jump. Line 6 shows T_{min} for the buckets worked out in the section "Practical Applications." Line 7 shows the conjugate tail water depth required for a hydraulic jump for the same Froude number and D_1 determined from the equation $\frac{D_2}{D_1} = 1/2\ (\sqrt{1 + 8F^2} - 1)$.

Table VIII

COMPARISON OF TAIL WATER DEPTHS REQUIRED FOR BUCKET AND HYDRAULIC JUMP

		Angostura Dam	Angostura Dam	Angostura Dam	Angostura Dam	Grand Coulee Dam	Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam
1	Q in thousands cfs	247	180	100	40	935	935	133	90
2	V_1 ft/sec	72	72	73	70	119	119	66	39

		Angostura Dam	Angostura Dam	Angostura Dam	Angostura Dam	Grand Coulee Dam	Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam
3	D_1 ft	12.5	9.1	5.0	2.1	5.3	5.3	7.6	3.6
4	F	3.6	4.3	5.7	8.5	9.1	9.1	4.2	3.7
5	T_{max} ft	70	72	88	125	101	175	99	31
6	T_{min} ft	67	60	46	34	73	80	50	20
7	T_{conj} ft	57	52	38	24	65	65	42	17
8	Bucket radius	47	39	26	12	30	50	35	12.5

The values in Line 6 are for the minimum allowable bucket radius. If a larger than minimum bucket radius is used, the required minimum tail water depth becomes greater, as shown in Line 8 for the two Grand Coulee bucket radii.

Summary of Bucket Design Procedures

The Angostura-type slotted bucket, Figure 1B, is well adapted for general use as an energy dissipator at the base of an overfall spillway. It is considered to be superior to the solid bucket in all respects. Wherever practical the higher teeth recommended in design Modification II, Figure 8, should be used. Also, wherever possible the elevation of the bucket invert should be placed above the channel bed so that the tail water depth above the bucket is close to the lower tail water limit, as in Figure 12A, for best performance.

Buckets are particularly suited to installations where an excess of tail water exists which would drown the hydraulic jump, or where deep excavation presents no problem.

The curves of Figures 19 through 24 should be used to obtain the essential dimensions for the Angostura-type slotted bucket. From the curves the minimum bucket radius, the required tail water depth, and the maximum permissible tail water depth can be determined, as illustrated in "Practical Applications" and summarized in Table VII. In addition, the tail water sweepout depth, which is an indication of the factor of safety of the bucket and its vertical placement, can be used to check the placement specifications. Figure 1 should be used to obtain the bucket dimensions after the radius has been established. Caution should be used in designing buckets for large structures such as 200-foot high spillways with discharges of 500 or more second-feet per foot of width, and low structures where tail water may submerge the spillway crest, without model verification. Model testing is desirable in all cases, however.

The design curves presented may also be used for determining the radius and tail water depth requirements for a solid bucket if for some reason it was desirable to use one.

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